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MASTER'S THESIS

Life cycle analysis of aluminum for use on a vessels hull

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Master in Maritime Operations: Maritime Technology and Management

Department of Maritime Studies

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02.06.2023

ABSTRACT

Due to the climate change the world is currently experiencing and the growing emphasis on the need to reduce greenhouse gas emissions, all stages of a fabrication and construction process should be evaluated to be as climate friendly as possible. In this thesis, aluminum has been considered as a hull construction material, more precisely the sea-resistant alloy 5083. The entire life cycle of aluminum is investigated, which includes the extraction of the raw material bauxite, electrolysis, and hot rolling. Additionally, along with the manufacture of the aluminum hull, as well as use, potential for repair, and recycling. A comparison of aluminum and steel as building materials for a vessels hull is another significant main point covered by the thesis.

In this thesis, comparisons between aluminum and steel are made in order to weigh the benefits and drawbacks in terms of price, emissions, energy consumption, strength, and weight. Aluminum's high price and significant energy consumption during production are drawbacks. While requiring significantly less energy to produce, steel is also much more affordable. Aluminum makes up for this later, though, with density that is one-third that of steel, and for vessels an increased speed, less fuel consumption, and even simpler operations will be achieved. Due to the density, less aluminum is required for the same construction than steel, and by comparing energy consumption per kg, the energy required for two similar hulls will not be as different after all. Aluminum has a higher scrap rate than steel, but both metals can be recycled with a significant reduction in energy use.

To examine the differences, carbon fiber, which is also a frequently used hull material, is being compared with steel and aluminum. Although carbon fiber has the advantages of having the lowest density and high strength, its costs and energy requirements are much higher. Moreover, recycling carbon fiber is more challenging and results in a significant loss of the material's strength.

Future strategies and solutions are presented and discussed in order to decrease energy use and emissions associated with aluminum production globally. Utilizing renewable energy sources, of which Norway is primarily a superior producer, must be a top priority.

Keywords: Aluminium, life cycle analysis, CO_2 footprint, energy consumption, vessel, aluminium hull, emissions.

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ABBREVIATIONS

A	Ampere
ASI	Aluminums Stewardship Initiative
CO_2	Carbon Dioxide
GHG	Greenhouse Gas
GLO	Global
GWP	Global warming potential
GJ	Giga joule
GPa	Giga Pascal
HAZ	Heat affected zone
IAI	The International Aluminium Institute’s
ISO	International Organization for Standardization
KRM	Karmøy Rolling Mill
kPa	Kilopascal
KTP	Karmøy Technology Pilot
kW/h	Kilo watts per hour
LCA	Life Cycle Analysis
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MRN	Mineração Rio do Nortes
MJ	Mega Joule
N/m^2	Newton per square meter
No_x	Nitrogen oxides
OIW	Oil in water
PAH	Polycyclic aromatic hydrocarbons

RoW	Rest of world
SOLAS	Safety of life at Sea
SO_2	Sulfur dioxide
SO_x	Sulfur oxides
SS	Suspended substance
U. S	United States
V	Volt

CHAPTER 1. INTRODUCTION

1.1 BACKGROUND

Aluminum is one of the most frequently used metals worldwide, and its demand is continuing to rise. Aluminum is adaptable and can be used for most things, including packaging, foil, soda cans, furniture and as construction material for buildings, aircraft, and ships. In addition to being completely impermeable and a superior reflector, aluminum also reflects heat and light. In comparison to other metals, aluminum requires less maintenance and replacement because of the oxide coating it forms when it reacts with oxygen. (Hydro, Fakta om aluminium, 2021).

Aluminum is a building material that can be customized for any product's intended use. The right aluminum alloys have the same strength and durability as steel while weighing only one-third as much; the density is 2,71 kg/m^3. Around 1.9 million tons of aluminum are produced annually by Hydro Aluminum (Bryhn & Gram, 2023), however it takes the same amount of energy to produce one ton of aluminum as a household uses in a year. (Sotere, 2022).

The need to limit CO_2 emissions is due to concerns about climate change and the impact it will have on the environment and society. High levels of CO_2 in the atmosphere leads to changes in the climate, such as rising temperatures, changes in precipitation patterns and increased sea levels, which in turn can have negative effects on ecosystems, societies, and economies. (Danbolt, 2022).

Climate change is a serious consequence of the emissions we produce in the world and, as a result, this imposes more stringent CO_2 emissions requirements. The Paris Agreement is an international agreement aimed at reducing climate change. Under the agreement, Norway has committed to reduce its emissions by up to 50 percent from 1990 levels by 2030. (Miljødirektoratet, 2022).

In this thesis, a “cradle to grave” life cycle assessment for aluminium is conducted, meaning that all stages of the materials lifecycle are considered, as illustrated in figure 1. All the phases of the lifecycle are to be examined; regarding environmental impacts, costs, and sustainability.

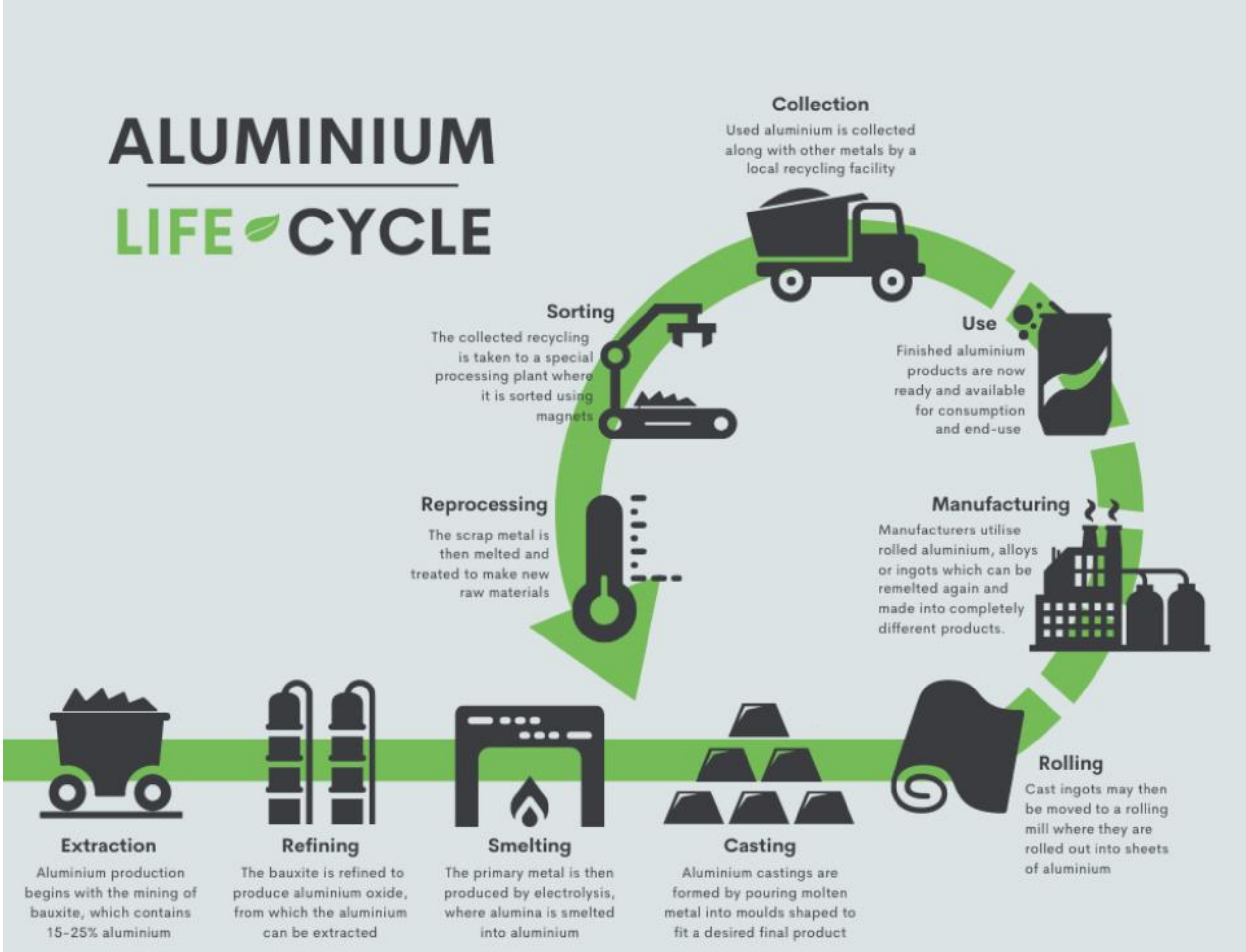


Figure 1 - Life cycle illustration of aluminum. (Aluminium Life Cycle, 2020)

The purpose of a life cycle analysis (LCA) is to provide a broad and comprehensive understanding of the environmental impacts the product has throughout its entire life cycle, from raw material extraction to disposal. By developing a life cycle assessment (LCA) for aluminum, it will be possible to determine which stages are most responsible for CO_2 emissions and other potential environmental issues. This will allow for the development of targeted mitigation strategies.

A LCA for aluminum aims to be a valuable tool for reducing the environmental impacts associated with the product and contributes to more sustainability in production and for consumption. Also, it can serve as a basis for decisions on the choice of materials used in the maritime industry, as it will provide a better basis for evaluating the totality in relation to other materials. (British Plastic Federation, u.d.).

According to Speira “Aluminum offers many positive properties that ensure optimal processing: High energy absorption, good formability, corrosion resistance and recyclability. In addition, it reduces both weight and production costs, while also helping to build high-quality and efficient ships and plant components. And still, despite the savings in weight, there is no loss in design strength - the structures of formed and welded semi-finished products offer exceptionally high torsional strength.” (Speira, 2023).

In the maritime industry, the typical construction material has been steel. Steel has been considered the strongest and best option to use. (RATSON Shipbuilding, 2019) The disadvantage of this material is the heavy weight, which contributes to weight restrictions. Extreme weather conditions also lead to corrosion of the steel, resulting in high maintenance costs. By comparison, aluminum is a suitable alternative material for the marine industry, where a weight saving of 50% can be achieved compared to steel. Aluminum will also have a longer lifespan and lower maintenance costs. (Hydro Aluminium, pp. 2,4,6,8 / 81).

Aluminum with the correct alloy, will have many properties that are suitable for the maritime environment. One hundred warships were built in aluminum with remarkable success and with significant weight savings as early as the early 1930s. Aluminum as a construction material provides an efficient combination of navigability, speed, economy, and weight. Aluminum has a good combination of lightness and strength, with high tensile strength and compared to steel, it has only one third of its specific weight. The material is easy to shape and extrude, which makes it easy to tailor solutions based on whatever the needs may be. (Hydro Aluminium, 2001, p. 22/83).

1.2 PREVIOUS WORK

According to a review of the literature, numerous theories with various methodologies and concerns have been developed regarding the life cycle of aluminum and greenhouse gas emissions. This section will include some examples of earlier work that is pertinent to the thesis' goals.

1.2.1 ELECTRICITY CONSUMPTION AND GHG EMISSION

Nunez and Jones (Nunez & Jones, 2015) conducted a study on behalf of The International Aluminum Institute's (IAI) to evaluate the life cycle of aluminum. The objective was to provide current data on the life cycle of aluminum for use in design and material selection. With the help of two different data sets, a cradle-to-gate model was developed; one involving the entire world (GLO) and the other for the rest of the world, excluding China (RoW). A partial life cycle impact assessment was conducted based on the following focus areas; "acidification potential, depletion of fossil energy resources, eutrophication potential, global warming potential, ozone depletion potential and photo-oxidant creation potential, along with water scarcity footprint of primary aluminium." (Nunez & Jones, 2015). From the study, the results shows that alumina refining and electrolysis, for both datasets, were the biggest greenhouse gas contributors. With higher values in the global dataset as a result of the inclusion of Chinese energy data and the increased share of coal-based electricity consumption that these data represent, it was discovered that electricity production contributes between 25% and 80% to all impact category indicator results. (Nunez & Jones, 2015).

Peng, Ou, Yan, and Wang (Peng, Ou, Yan, & Wang, 2019) conducted a study for the life cycle perspective regarding greenhouse gas emissions (GHG) and energy consumption from primary aluminium and recycled aluminium production in China. The study compares and contrasts China and The United States (US). According to the findings, China's energy consumption and greenhouse gas emissions are about twice as high as those of the US, due to the coal generated electricity used by China. In comparison to the production of primary aluminum, recycled aluminum uses a great deal less energy and emits far fewer greenhouse gases over its entire life cycle. Conclusion: Given their positive effects on aluminum's ability to perform over its entire life cycle, the recycled aluminum industry and the low-carbon electricity used for aluminum electrolysis should be encouraged. (Peng, Ou, Yan, & Wang, 2019).

Haraldsson (Haraldsson, 2020) conducted a study focusing on the supply chains and the energy efficiency in the aluminum industry, with a view to examining potential energy efficiency measures to lower industrial GHG emissions. The study was conducted using a review of the literature, focus groups, surveys, and calculations of the effects on primary energy use, greenhouse gas emissions, and energy and CO_2 costs. (Haraldsson, 2020). The study showed that cooperation and communication between the companies were crucial for achieving energy efficiency and identified a number of measures that could be used to improve energy efficiency. The study also demonstrated that significant obstacles to energy efficiency include a variety of risks, as well as the costs associated with production halts, intricate production procedures, and technology that is inappropriate for the location. (Haraldsson, 2020).

1.2.2 POLLUTION AND WASTE PRODUCTION

Abdollahi, Emrani, Chahkandi, Montazeri, Aghlmand and Gheibi (Abdollahi, et al., 2021) conducted a study that investigates the life cycle of aluminum production and analyzes how much gaseous pollution and solid waste are produced in various production units. Additionally, the study also investigates the systems for reducing pollution: "Sedimentation chamber, internal separators, cyclones, fabric filters, electrostatic precipitators, and wet collectors in particle removal and condensation, absorption, adsorption, incineration, and wet washing in SO_2 and NO_x removal were reviewed and ranked by using ELECTRE, TOPSIS, and SAW methods." (Abdollahi, et al., 2021). The outcomes demonstrate that cyclones are more effective at removing particles than wet washing systems for removing SO_2 and adsorption for removing NO_x. (Abdollahi, et al., 2021).

Wang (Wang, 2016) conducted a report on the findings of the life cycle inventory (LCI) and life cycle impact assessment (LCIA) of aluminum products made in North America in the production year of 2016. The objective was to give current knowledge about the potential environmental effects of aluminum products. Production information from over 100 production facilities was gathered, and LCA models were developed using the cut-off method and a net scrap substitution method (a variation of the substitution method). (Wang, 2016).

1.2.3 USE OF ALUMINIUM

Benson and Downes (Benson & Downes, 2011) conducted a study regarding "the strength of a number of unstiffened aluminum plates with material and geometric parameters typical of the midship scantlings of a high-speed vessel using a nonlinear finite element approach. According to the studies, these variables can have a big impact on how the plates behave in terms of strength both before and after the collapse point has been reached. " (Benson & Downes, 2011).

1.3 MOTIVATION OF RESEACH

This master's thesis has been written as the conclusion of the master's study Maritime Operations at the Norwegian University of Applied Sciences.

Sustainability and the desire for a lower CO_2 footprint are the driving forces behind this thesis. Aluminum has the ability to be a suitable construction material for vessel hulls, and the thesis wants to shed light on the entirety of the material with its total environmental footprint, while comparing it to steel.

1.4 PURPOSE OF STUDY, METHOD, AND RESEARCH QUESTION

In this thesis, all stages of aluminum vessel hull production, from the raw material to the product, will be considered. The main purpose is to evaluate whether aluminum is a suitable alternative construction material for vessels hull relative to other materials used today, specifically steel, based on an entire life cycle evaluation. Costs, environmental impacts, emissions, and sustainability are key areas of interest that help provide a comprehensive view of the entire life cycle of aluminum. Considering that steel is thought to be the strongest material, it is most frequently used to build hulls. However, aluminums life cycle, from cradle to grave will be evaluated based on costs, emissions, maintenance, strength, weight, and recycling abilities.

The research questions are given as follows:

- Does aluminum make a good construction material for a vessels hull based on the life cycle analysis, and can it compete with steel?

- Are there specific advantages associated with aluminum that could be beneficial to the hull of a ship?

The thesis compares aluminum to steel, assesses the differences, and weighs the advantages and disadvantages of both materials. The thesis will base its findings on the use of aluminum alloy 5083, which is a seawater-resistant, sustainable, easy-to-work with, material aluminum alloy designed for maritime conditions. Since the material is to be used on vessels hull and in maritime conditions, the plates need to be thick and sufficient strong, therefore the plates are hot milled at up to 12mm in thickness and with widths up to 2500mm.

The research method consists of evaluating:

- The process of making the hull is to be examined and documented, as well as how the hull handles being in operation in a maritime environment.
- How can potential damage to the hull be repaired, and how should maintenance work during operations be carried out? These are important questions that will be examined.
- Examining aluminum from a financial standpoint and contrasting it with steel allows for comparisons of the capital and ongoing costs.
- An important focus today is sustainability and in that regard aluminum’s recycling properties will be highlighted and documented.
- The thesis also looks at some comparisons of aluminum and carbon fiber as hull building materials, albeit to a lesser extent.

1.5 LIMITATIONS

This thesis covers the production of aluminum by Hydro Aluminum, along with rolling and recycling at Speira AS, at production sites in Karmøy and in Germany. Aluminum hull production is not restricted to the use of a specific type of vessel but is discussed in a general form. The thesis collects data from technologies and practices currently employed by these businesses and points to goals and solutions for further use of the material.

1.6 THESIS STRUCTURE

In five different chapters, the research questions connected to this thesis have been analyzed and addressed. The summery of the chapters in the research are;

- **Chapter 1** introduces the background for life cycle analysis and explains why aluminum is an option for vessels hull construction. It gives insight about the motivation, purpose, previous work, and the research questions associated with this thesis.

- **Chapter 2** discusses the theoretical background of aluminum, and describes the entire production process, which includes raw material extraction, electrolysis, and rolling.

- **Chapter 3** discusses the manufacturing of aluminum hulls, the operations and applications of aluminium hull, maintenance, and repair options in case of damage.

- **Chapter 4** is examining the potential for recycling aluminum and which necessary steps are required to carry this out. In addition, the economic viewpoint is covered, and the current emission situation is shown, along with a comparison to steel.

- **Chapter 5** presents a comprehensive overview of the contrast between steel and aluminum, along with several potential future actions that could be taken to reduce emissions and energy use. Along with a conclusion regarding the findings from the research about the life cycle of aluminum and the environmental impacts.

CHAPTER 2. THEORETHICAL BACKGROUND OF ALUMINIUM

2.1 EXTRACTION OF RAW MATERIAL

Aluminum is an element, with atomic number 13 in the periodic table, (Pedersen & Kaland, 2023) as shown in figure 2. It is a silver shiny looking metal, and the third most common chemical element on the planet. Remarkably, about 75 % of all the aluminum produced in the world, is still in use today. (UC RUSAL, u.d.)

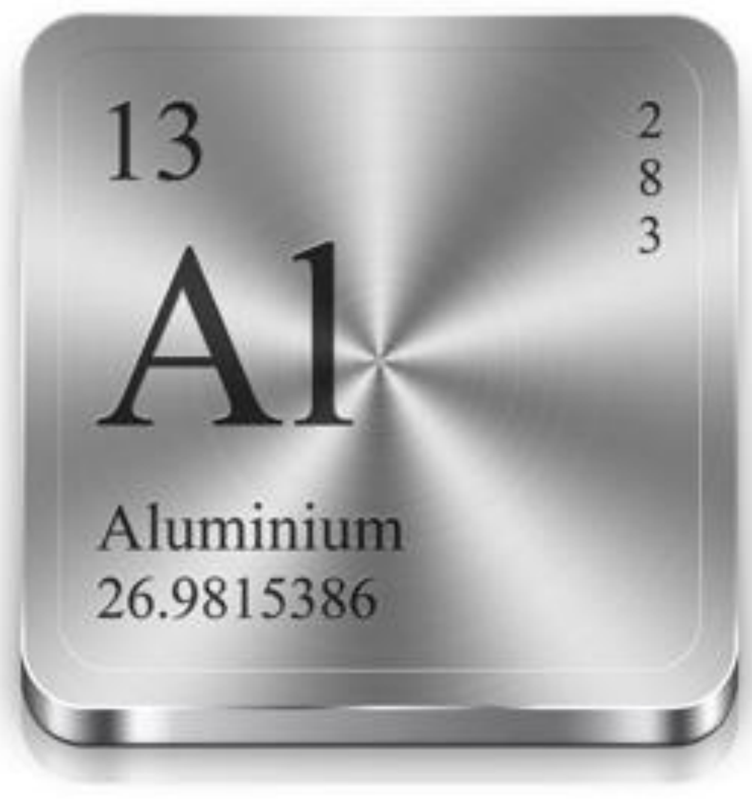


Figure 2 - The element Aluminum (UC RUSAL, u.d.)

8% of the soil and rocks on the planet are made of the element aluminum. It does not exist in its purest form but is produced through an intricate process. (Thyssenkryupp, 2023). The primary source of aluminum is the soil type bauxite, which is similar to clay and is found in rocks located in warm climates. Brazil, Guinea, Jamaica, and Australia are the top bauxite exporters, and Hydro Aluminum, Norway, uses bauxite produced in Brazil. (Thyssenkryupp, 2023)

Figure 3 - Bauxite. (ASA, Norsk Hydro, 2023)

Over the course of several million years, the chemical breakdown of rocks containing aluminum silicates produces bauxite as a byproduct. (ASA, Norsk Hydro, 2023) Typically, it has a reddish-brown color and contains a mixture of aluminum oxides minerals along with impurities, as shown in figure 3. The content may be in various mixtures, like iron, silicon, titanium, sulphur, gallium, chromium, vanadium oxides, as well as sulphurous calcium, iron, and magnesium carbonates can all be found in bauxite along with aluminum hydroxide. (UC RUSAL, u.d.)

The Bayer Process is used to separate the aluminum oxide (alumina) from the bauxite. Figure 4 illustrates the various steps that must be taken in this process;

- Digestion
- Clarification
- Precipitation
- Calcination

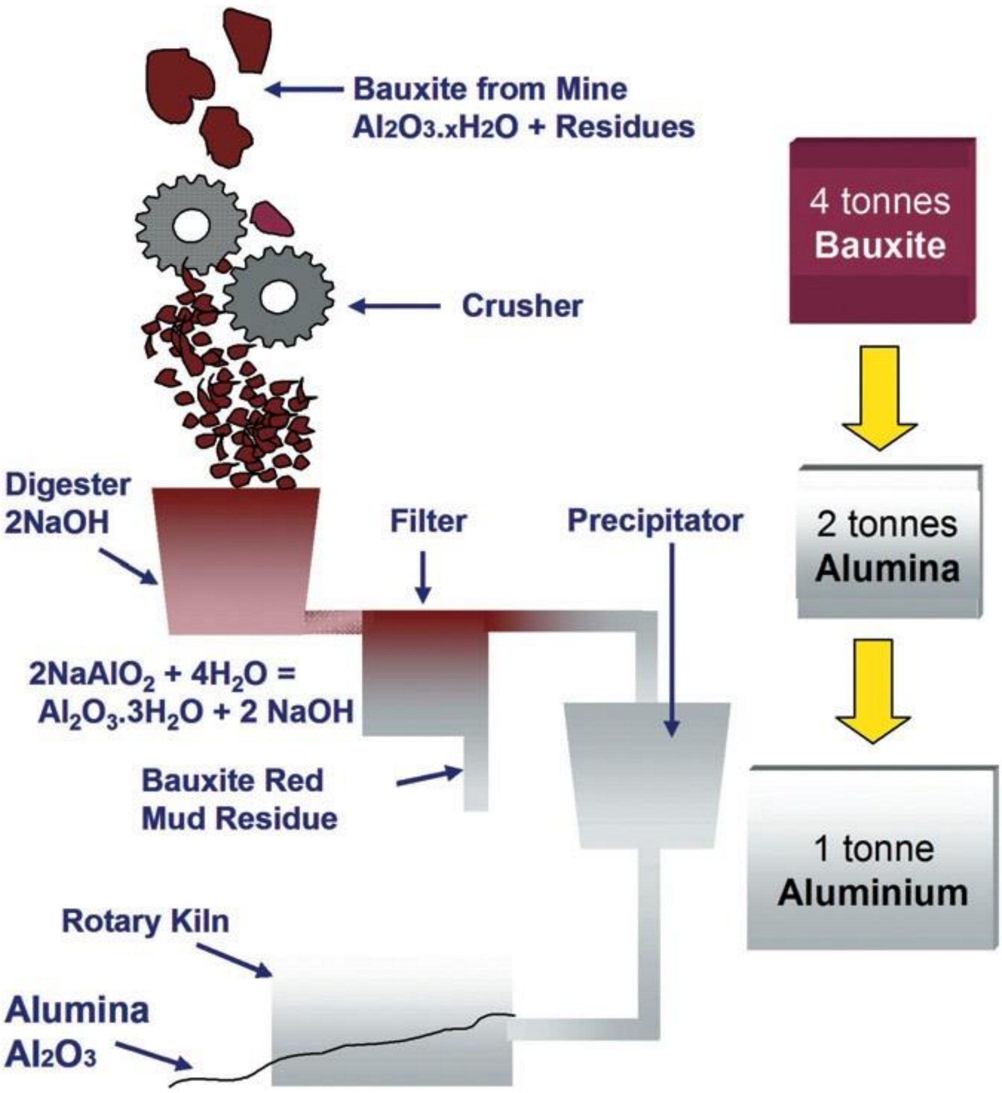


Figure 4 - Refining bauxite. (Panalytical & AZO Materials, 2020)

Digestion - The stone is first digested into soil, then heated with sodium hydroxide to a temperature of roughly 150–200 degrees Celsius, where alumina and silica is dissolved. (World of Chemicals, 2023).

Gibbsite (Al $(OH)_3$), boehmite (AlOOH), and diaspore (-AlO (OH)) are the three aluminum compounds that are present in bauxite. (World of Chemicals, 2023).

Filtration - The mixture is then filtered to get rid of unwanted particles and impurities. The extra red mud settles at the bottom before being released. (World of Chemicals, 2023). The equation states that the filtration process changes the aluminum oxide into soluble sodium aluminates, $2NaAlO_2$: $Al_2O_3 + 2NaOH \rightarrow 2NaAlO_2 + H_2O$. (World of Chemicals, 2023).

Precipitation - Utilizing heat exchangers, the heated mixture is converted into a cool liquor during the precipitation process. Aluminum hydroxide crystals are found, and the heat is causing silica to precipitate. (World of Chemicals, 2023).

Calcination – A rotating kiln with a temperature range of 1010–1260 degrees Celsius is used to wash, dry, and heat the alumina hydroxide crystals. 90% of the generated gibbsite is transformed into alumina. (World of Chemicals, 2023).

$2\,Al(OH)_3 \rightarrow Al_2O_3 + 3\,H_2O$.

In figure 5 the product of the Bayer process, alumina, are presented. Alumina contributes as the primary ingredient in the production of aluminum. It is a white, fine-grained powder.

Figure 5 - Alumina. (Hydro, Alumina, 2023)

Transport is necessary to get the alumina to Hydro's manufacturing facilities after it has been extracted and separated from the bauxite as a product. Alumina is shipped by ship from Brazil to Norway and then to the harbor at Karmøy to be used in the production operations there.

There are a number of reasons why alumina needs to be kept dry. The first rule is to never add moisture to an electrolysis cell due to the fact that the water can expand about 1,500 times in that heat, which can cause an explosion. Therefore, it is crucial to maintain the alumina's total dryness prior to its addition to the production process. In order to prevent it from blending with rainwater or other liquids, it is also crucial to keep alumina dry during storage and while being transported. In that case, the powder might gather at the tank's bottom and losh when the vessel rolls. Such an imbalance would be undesirable for the stability of the ship under transport for safety reasons.

2.1.1 ENVIRONMENTAL IMPACTS OF BAUXITE PRODUCTION

Every year, Hydro Aluminum imports about ten million tons of bauxite from Brazil for use in making aluminum. This number will continue to rise in accordance with the global demand for aluminum. For extraction of the bauxite, forest must be cleared, and massive amounts of stone and clay must be removed in order to gain access to the extraction site, which is 10-15 meters below surface, as can be seen in figure 6. Outside of the rainy season, from May to November, four to five square meters of forest, or about six hundred football fields, are removed during the bauxite excavation process. Note that, it may take up to 150 years for the area to fully recover. (Nickelsen, 2019). When the construction site is cleared, it is refilled with soil masses in an effort to encourage the emergence of new plant life, something that Hydro is actively pursuing. (Nickelsen, 2019).

Figure 6 - Extraction of Bauxite in Brazil. (Nickelsen, 2019).

The Christian Aid report, “Profit before people and planet - How public economic policies and corporate profit maximization perpetuate the unsustainable exploitation of the Brazilian Amazon and its people,” states that bauxite mining has contributed to:

> “Deforestation of extensive areas of the Amazon Forest and serious adverse human rights and environmental impacts on Quilombola and riverine communities. Mineração Rio do Nortes (MRN) mining operations have polluted watercourses, hindering the access of these communities to good quality water, generating diseases, and impacting on fishing activity, and deforestation by MRN’s mining operations has affected access to food and natural resources that support livelihoods for these marginalized communities.” (Aid, 2022).

Both the local population and the environment have suffered as a result of bauxite extraction and alumina production. Occasionally, the water quality in the vicinity of the production site was bad and unsafe. Some people and animals are compelled to leave the areas. The nearby Taua people was forcibly relocated in 2017 as a result of Hydro’s production. (Latin-amerikagruppene i Norge, 2021).

Brazil's Ministry of Health reported in 2018 that the drinking water from up to about two kilometers away was contaminated with elevated levels of lead, sodium, and other harmful substances. (Teknisk Ukeblad, 2018). As a result, Hydro made an agreement with Brazil, to make a number of investments, including technical upgrades at Alunorte (figure 7), philanthropic contributions, and the development of water treatment facilities to reduce pollution. (Nilsen, 2018).

In Barcarena, in the state of Pará, is Hydro Alunorte, the second-largest alumina refinery in the world, which is shown in Figure 7. “Bauxite for Alunorte is obtained from Mineraço Paragominas via a pipeline and from Mineraço Rio do Norte (MRN) via "Vila do Conde" port”. (Hydro, 2023). A portion of the alumina produced is exported, and a second portion is sent to the Albras plant in Barcarena, which makes aluminum ingots. (Hydro, 2023).

Figure 7 - Hydro's aluminum refinery, Alunorte, in Brazil. (Valvik, 2018)

The operations of Hydro in Brazil are still at odds with the locals there as of the time of writing. Five years prior, a flood brought on by a lot of rain caused destruction and tainted drinking water in the region. The locals accuse Hydro of discharging red sludge, a byproduct of the production of aluminum, but Hydro maintains that their production is not to blame. The area's poor residents complain about the quality of their air and water, which has a significant negative impact on the Indigenous people's rights and standard of living. (Rustad & Kleeb, 2023).

Hydro has acted by providing clean drinking water to the local families, despite the fact that they do not believe they are to blame for the pollution. Over 40,000 residents have filed a significant lawsuit against Hydro that covers both the pollution that occurred five years ago as well as the ongoing emissions the production has. Hydro production in Brazil emits 5.5 million tons of CO_2 annually, which, in comparison, is 10% of all annual emissions in Norway. (Rustad & Kleeb, 2023).

2.2 ELECTROLYSIS

Aluminum is produced through a process called The Hall-Héroult process which relies on electrolysis and carbon reduction as its main principles. It is a continuous process that runs around-the-clock throughout the entire year and is conducted in electrolysis cells that are linked in series to create electrical reduction lines in an electrolysis potroom, as shown in figure 8. (Haraldsson, 2020, p. 28/149).

Figure 8 - Aluminium electrolysis potroom. (Kvande, 2014)

Electrolysis uses direct current, which consumes a lot of electrical energy at low voltage—roughly 150 000 A at 4 V per cell. (Nagwa, 2023) The temperature is about 900 - 1000 degrees. The cathode is constructed from a steel shell with a tub-like shape, lined with heat-resistant bricks, and covered with a layer of carbon that serves as the negative cathode during the electrolysis process. (Nagwa, 2023) An illustration of an electrolysis cell is shown in figure 9 below. The carbon-based anodes are submerged in a solution of cryolite (Na_3AlF_6), calcium fluoride (CaF_2), and sodium fluoride (NaF), to which aluminum oxide is added and dissolved. When oxygen and carbon monoxide react at the graphite anode, liquid aluminum is created, which sinks to the cathode's bottom. (Universitetet i Oslo, u.d.).

The chemical reaction equation; ***$2Al_2O_3 + 3C \rightarrow 4Al + 3CO_2$***

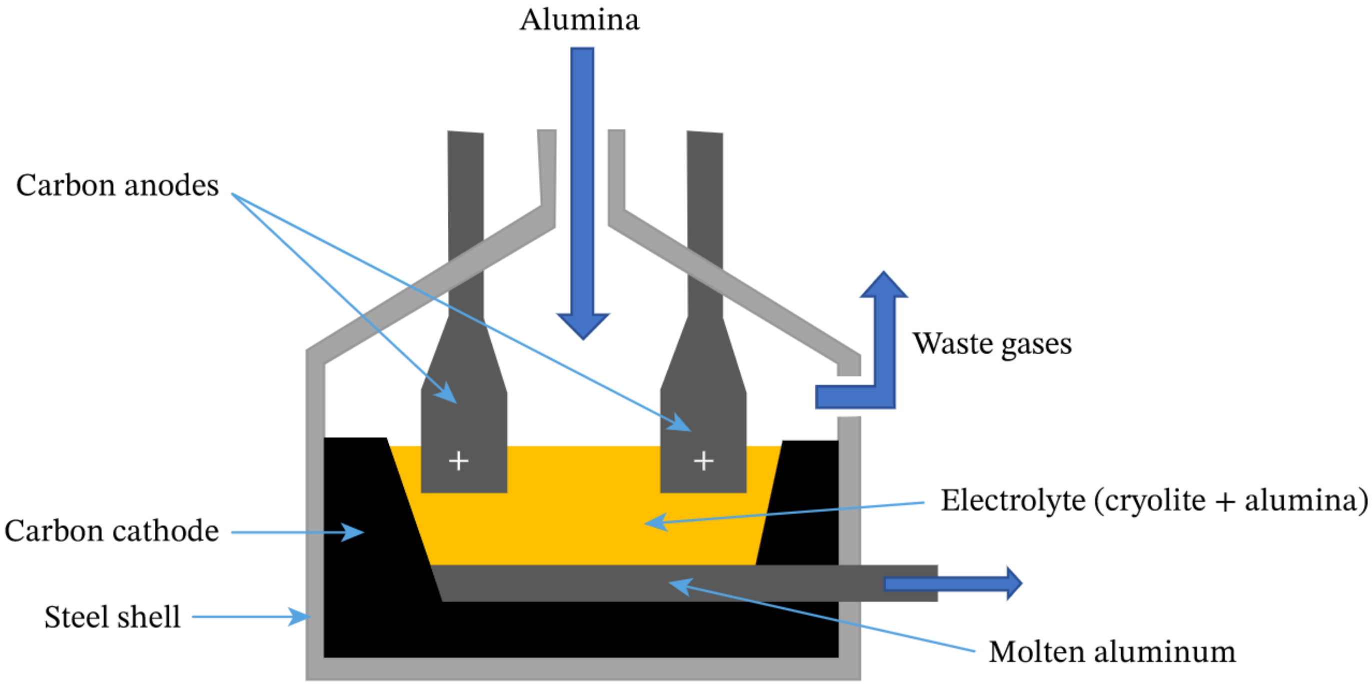


Figure 9 - A electrolysis cell. (Nagwa, 2023).

The electrons are moving during the electrolysis process in terms of oxidation and reduction. Aluminum ions are drawn to the cathode during the process, where they are reduced, given three electrons each, and transformed into aluminum metal atoms, which then fall to the bottom of the cell. The negatively charged oxide ions travel to the anode, where they undergo oxidation. During this process, each oxide ion loses two electrons, which they then combine to form oxygen molecules. (Nagwa, 2023).

For the electrolysis of the alumina, the half-equations and overall equation for the chemical reactions (where *l* = liquid, *g* = gas, *s* = solid) are (Nagwa, 2023);

$$Al^{3+}(l) + 3e^{-} \rightarrow Al(l)$$

$$20^{2-}(l) \rightarrow O_2(g) + 4e^{-}$$

These two half-equations are needed to get an overall equation and the number of electrons on each side of the equation needs to be equal and balanced (Nagwa, 2023):

$$4Al^{3+}(l) + 12e^{-} \rightarrow 4Al(l)$$

$$6O^{2-}(l) \rightarrow 3O_2(g) + 12\ e^{-}$$

Which results in;

$$2Al_2O_3(l) \rightarrow 4\ Al(l) + 3O_2(g)$$

The reaction between the carbon anodes and the generated oxygen results in the production of carbon dioxide because of the elevated temperature inside the cell (Nagwa, 2023);

$$C(s) + O_2(g) \rightarrow CO_2(g)$$

Figure 10 - A specialized vehicle for transporting liquid aluminum. (Aluminium INSIDER, 2023)

A suction pipe is lead down into the cathode to obtain the aluminum in a crucible, this is done from a vehicle designed specifically for transporting liquid aluminum, shown in figure 10.

An electrolysis cell can be any size, and the ones Hydro has on Karmøy for its technology pilot (a production pilot with a special technology for reduction of energy consumption and emissions) are about 18 meters in length. While the cathodes of an electrolysis cell have a lifespan of roughly 5-7 years, the anodes need to be replaced about every 30 days. The process must be conducted in closed systems in order to minimize emissions and heat loss. The cells are lined tightly as a mitigating measure, and fluorine is recycled and returned to the electrolysis bath as much as possible. Two tons of aluminum oxide are required in order to produce one ton of aluminum.

Figure 11 - Karmøy Technology pilot. (Hydro, 2020).

The amount of energy used is about 12,3 kWh/kg Al and the direct level of CO_2 emissions from Karmøy's technology pilot (KTP) production are about 1,45 CO_2/kg Al. (Hydro, 2020).

The production site, like KTP in Karmøy, shown in figure 11, typically has a warm climate because of the high temperature in the electrolysis cells. The protective gear that employees in the production industry must wear is strictly regulated, and this equipment includes layers of clothing made of a special fabric that can, to some extent, withstand splash damage from liquid metal. Full-coverage clothing and safety footwear are required, as well as thick socks that could dissolve if they come into contact with liquid metal. It is necessary to wear safety gear like brontugard gloves that can prevent burns when coming into contact with a hot surface because they can withstand extreme heat, along with a breathing mask with a protective filter against polluted air, safety glasses, and a helmet with neck protection.

Due to the heat generated by the cells, the area between them is warm; however, contact with hot surfaces should be avoided as this could result in burns. When working with liquid metal, it's also necessary to wear a protective aluminum coat that can shield the user from metal splashes and a protective helmet screen that can shield the user's face. Additionally, it's crucial to keep water away from liquid aluminum because it can expand up to 1500 times and result in an explosion.

A magnetic field develops around the electrolysis cells as a result of the substantial amount of electricity needed to produce aluminum. Although it has not been demonstrated that this is harmful to humans, it is not advisable for pregnant women to stay in the area for safety reasons. Due to the strong magnetic field and potential interference with pacemakers, people who live with peacemakers are unable to enter or remain in the area. When handling equipment, it is also crucial to keep the magnetic field in mind. You must be sufficiently aware of how things are affected by the magnetic field in order to be able to take the appropriate safety precautions. Equipment, vehicles, and electronics can all be impacted by the magnetic field.

Working in an electrolysis production site calls for specialized knowledge and training. Working in this manner should be safe as long as the regulations are followed, and safety equipment is used properly. Protective masks are required in accordance with the results of routine air quality inspections conducted inside the production site.

2.2.1 CARBON ANODE PRODUCTION

The use of anodes is a significant factor in the production of aluminum. These, which have a lifespan of about 30 days and must be replaced frequently, are regarded as essential consumables. The size and design of an electrolysis cell determine how many anodes it contains. Hydro manufactures and bakes finished anodes in its own anode factory in Norway. Hydro also purchases anodes from other parts of the world, like China, based on supply, capacity, and price. Coal tar pitch, which serves as the binder, is mixed, and kneaded with dry aggregate to create anode paste during the production of the anodes. This dry aggregate contains petroleum coke, rejected green and baked anodes, and butts. After that, the anode paste is compacted in a vibro-compactor or a press to make green anodes, which are baked in sizable furnaces at high temperature approximately around 1200 degrees, to create baked anodes. From the time the green anodes are inserted until they are fully burned anodes, it takes about 14 days. (Amrani, et al., 2021) (Rustad T. , 2021). The production process for making anodes is shown in Figure 12.

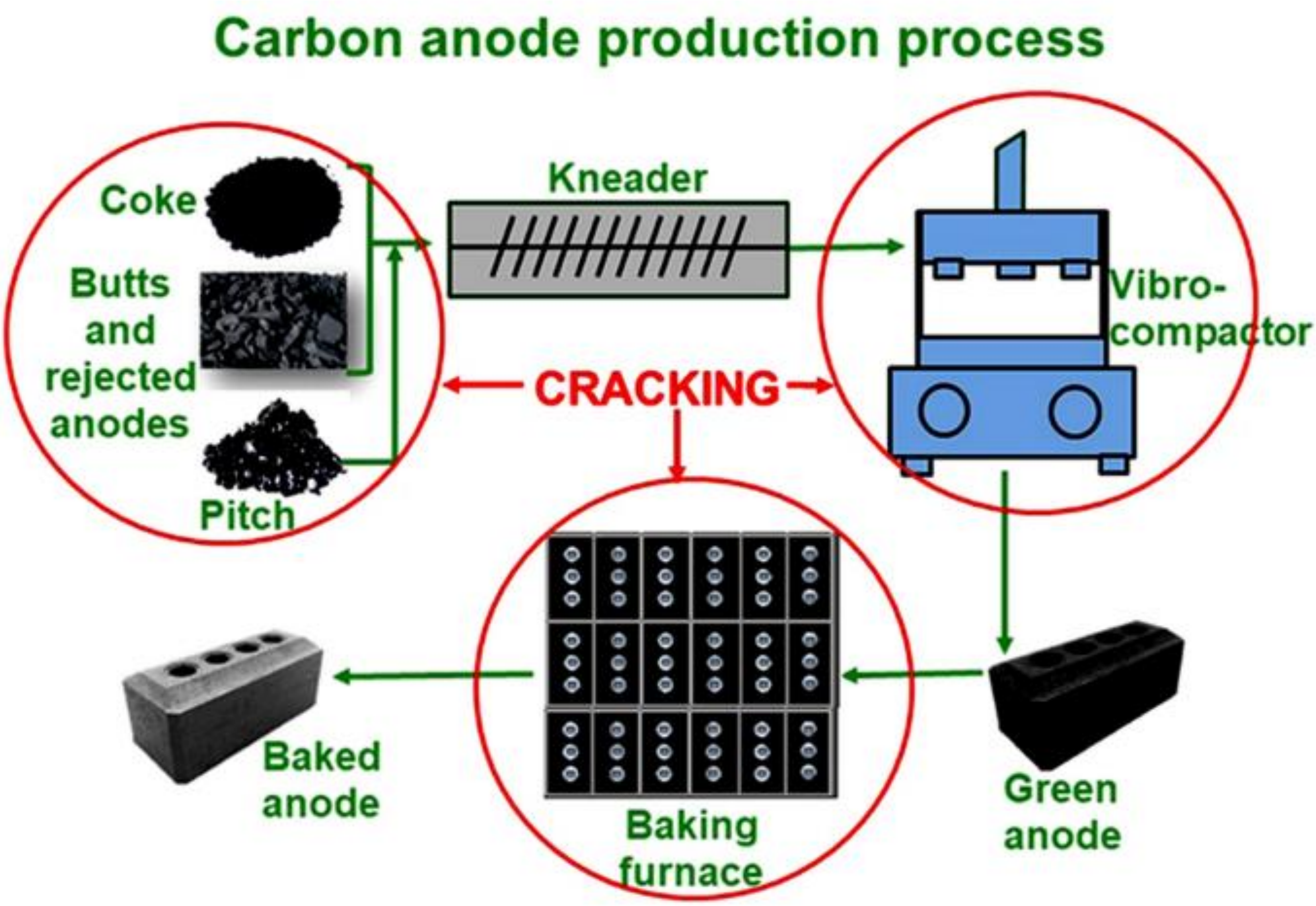


Figure 12 - Carbon anode production process. (Amrani, et al., 2021)

Anodes are priced at around NOK 4,800 per ton (Made-in-china, 1998-2023) when bought in China, though costs can vary slightly depending on quality and the market. Anode production is stated to require a typical specific energy consumption of between 2-3 GJ/t_{anodes}, according to the study "Specific energy consumption in anode bake furnaces." Depending on the process equipment and process control, energy consumption varies to some extent. (Keller, Sulger, Meier, Severo, & Gusberti, 2010).

2.2.2 ENVIRONMENTAL IMPACTS OF ELECTROLYSIS

Around 2%, or 1.3 million tons, of the total 65 million tons of aluminum produced globally in 2020 were produced in Norway. Since each metal atom produced generates three-quarters of a CO_2 molecule, the production process results in a byproduct emission of 1.5 tons of CO_2 gas per ton of aluminum. (Senanu, Skybakmoen, & Solheim, 2021) A total of two million tons of CO_2 were released into the atmosphere as a result of Norway's aluminum production in 2020, or 4% of the country's overall CO_2 emissions. In addition to using a sizeable amount of electricity, the production of aluminum uses more than 13% of Norway's annual hydropower output, or about the same daily amount of electricity as 2,000 to 3,000 households use in a year. (Senanu, Skybakmoen, & Solheim, 2021)

The environmental challenges aluminum production in Norway poses, are all covered in a 1995 project for impact studies of industrial emissions from primary aluminum works in Norway. Fortunately, the emphasis on the environment has led to the development of better solutions and the introduction of emission-reduction measures, but several aspects of this report's findings still remain relevant today.

The exhaust gases from aluminum production contain dust, $S0_2$, CO_2, CO, and some small amounts of tarry substances, of which approximately 20% are PAH. The term "PAH" refers to a group of potentially cancer-causing substances. Fluoride is emitted in both dust and gaseous form, with the gaseous form being the most harmful to plants and wildlife. (Hydro Aluminium a.s, Elkem Aluminium ANS, Sør-Norge Aluminium AlS., 1995). The majority of substances like fluoride, dust, and PAH are removed from dry cleaning facilities by adding aluminum oxide, which is then filtered through large bag filters. A reduced loss of fluoride occurs as a result of the secondary oxide's subsequent reuse. $S0_2$, PAH, fluoride, and dust exhaust gases can be effectively removed up to 99% using wet cleaning facilities with seawater or lye. As a result, the production hall ventilation air is the main source of fluoride removal. (Hydro Aluminium a.s, Elkem Aluminium ANS, Sør-Norge Aluminium AlS., 1995).

In Norway, businesses with emissions are required to have a permit for all air and water emissions. The emission components are expressly regulated through specific conditions in Hydro's pollution permit.

For emissions to air, Hydro at Karmøy conducts measures for:

- Fluoride
- Dust
- SO_2
- Heavy metals
- Diffuse dust emissions to air

For emissions to water, Hydro at Karmøy conducts measures for:

- SS-suspended substance
- PAH-polycyclic aromatic hydrocarbons
- Heavy metals
- Oil in water (OIW)
- Diffuse dust emissions to water

Within the factory area, Hydro Karmøy has two settling basins and two catch ponds. For the purpose of regulating discharges to the sea, these are followed up with routine measurements. Additionally, the catch ponds and pools are inspected every day. The water level is visually inspected, and any obvious contamination on the surface is noted. (Assadian, 2022).

In addition, Hydro Karmøy must have control over the following:

- Measurements of external noise are performed.
- Water monitoring of the nearby sea, including every two years a check for environmental toxins in mussels and every six years a check for environmental toxins in sediment.
- Fluoride concentrations in grass and twigs. During the growing season, samples of the vegetation are collected three times annually.
- Annual fluoride testing is done on animals that graze close to the factory.
- Monitoring of closed landfills and contaminated land in accordance with the measurement program.

• An annual review of waste management, including both common and hazardous waste, is done. Annual reports of waste production are made to the authorities. (Assadian, 2022).

Numerous measurements are made at various emission points to ensure that the pollution permit is being followed in order to control the production's emissions to the outside environment. According to the agreement, all limit values must be upheld, and the company is required to reduce emissions as much as it can without incurring undue expenses. (Assadian, 2022). The business must make sure that equipment that could affect emissions is maintained in a preventative manner in order to keep routine emissions as low as possible and prevent unintentional emissions. It is necessary to record procedures and the maintenance system for this type of equipment. It must take the steps required to eliminate or significantly reduce the risk of increased pollution, while staying within reasonable bounds, if there is a risk of increased pollution. Conditions that could significantly increase pollution or pose a risk of pollution must also be reported to the appropriate authorities. (Assadian, 2022).

Figures 13 and 14 display a graph of the CO_2 and fluorine emissions from Hydro Karmøy over a number of years. Despite a rise in production, the trend is declining. Better technology and methods for producing and managing the emissions it causes are some of the factors contributing to a trend of declining emissions. For the purpose of regulating and enhancing emissions, all emission in Norway must be closely tracked and reported. (Assadian, 2022).

Emissions of Carbon dioxide (CO_2) (in 1000 tons per year)

Hydro Aluminum Karmøy

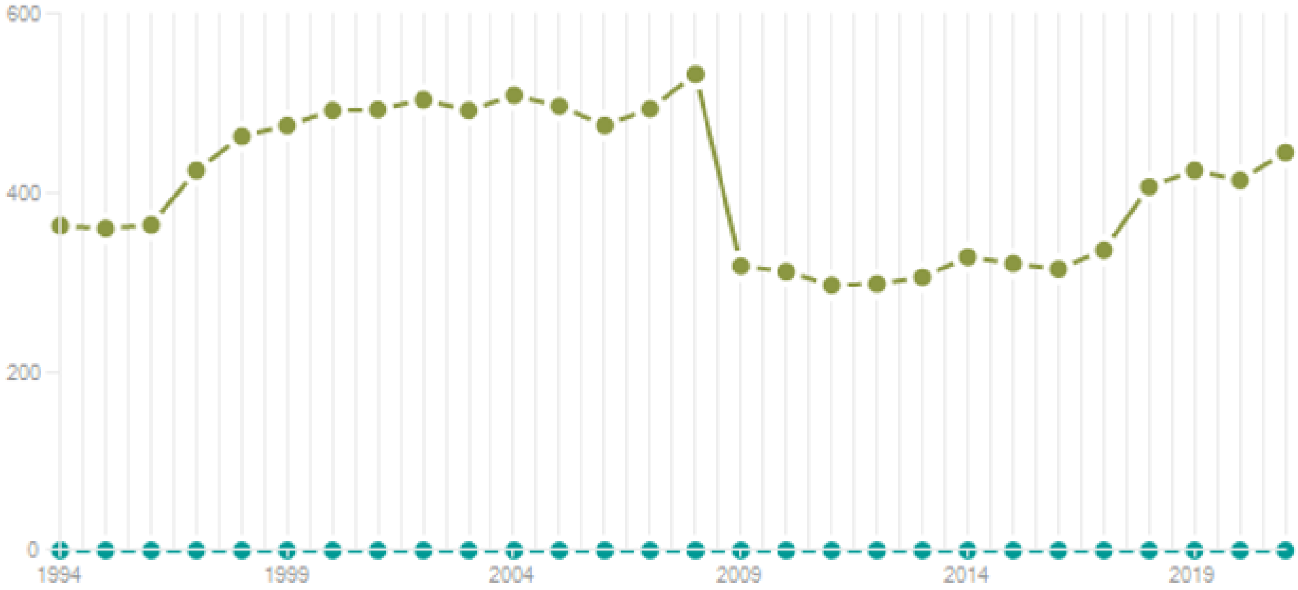


Figure 13 - Emissions of Carbon dioxide (CO2) at Hydro Karmøy. (MILJØDIREKTORATET, 2021)

Emissions of Fluorine (FLUORINE) (in 1000 tons per year)

Hydro Aluminum Karmøy

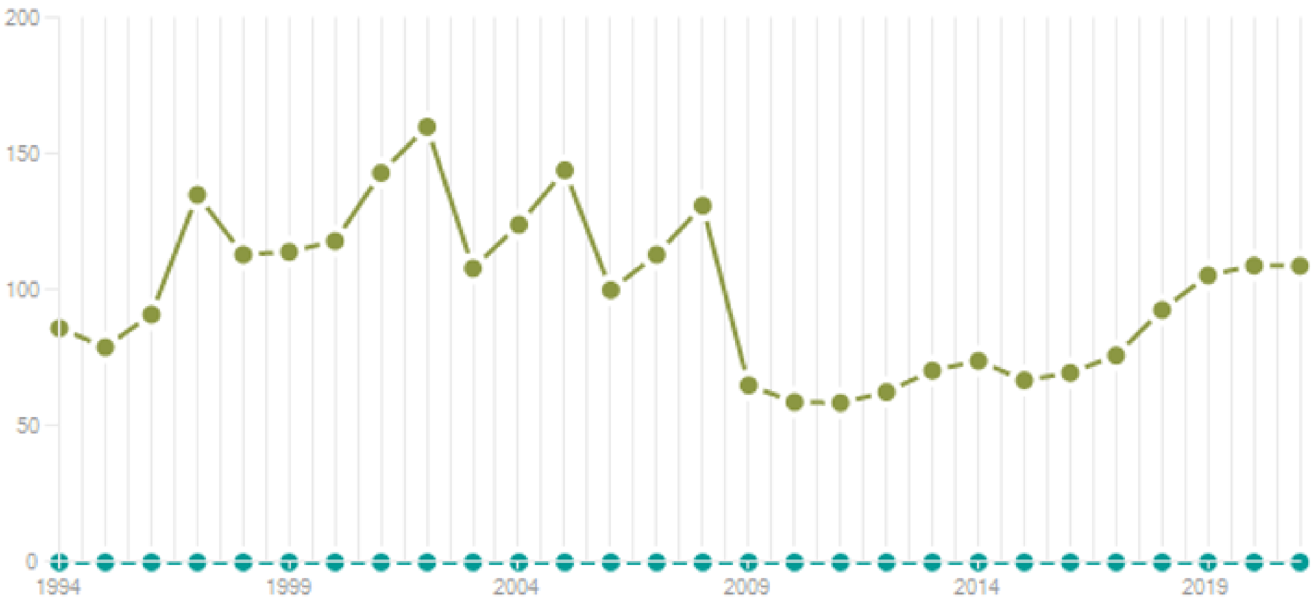


Figure 14 - Emissions of fluorine at Hydro Karmøy. (MILJØDIREKTORATET, 2021)

In contrast to many other nations that prefer to use coal and gas power, Norway produces aluminum using renewable energy sources. It is advantageous to use Norway as a production nation because renewable energy sources will only contribute to 20% of the emissions from a coal-fired power plant. The total CO_2 footprint for one ton of aluminum, from the mine to the finished product, is under four tons. (Senanu, Skybakmoen, & Solheim, 2021)

2.2.3 STANDARDS

Today's businesses frequently adhere to a number of standards in order to carry out the production processes in a dependable and high-quality manner. The businesses Hydro and Speira are ISO-certified, and they adhere to a number of the pertinent standards. The goal of ISO, a global organization for standardization, is to establish global regulations for the quality assurance of goods, services, and processes. They are made up of 160 members from various nations, each of whom represents ISO in their own nation. (RISMA, 2023).

The Hydro Quality System makes sure that their production facilities uphold the certification standards; in addition, this may involve additional, more specialized standards needed for certain customer groups. (Hydro, 2023). The included standards are;

- *"ISO 9001 and 14001*
- *ISO TS-16949 automotive standard specification*
- *Quality assurance mechanical certifications*
- *ABS quality certification*
- *Full-service quality assurance laboratory"*

  (Hydro, 2023)

Speira, which is managing the rolling and recycling processes, is also pursuing an ambitious sustainability strategy with a strong emphasis on the CO_2 footprint and transparency of the products and operations in order to safeguard the environment.

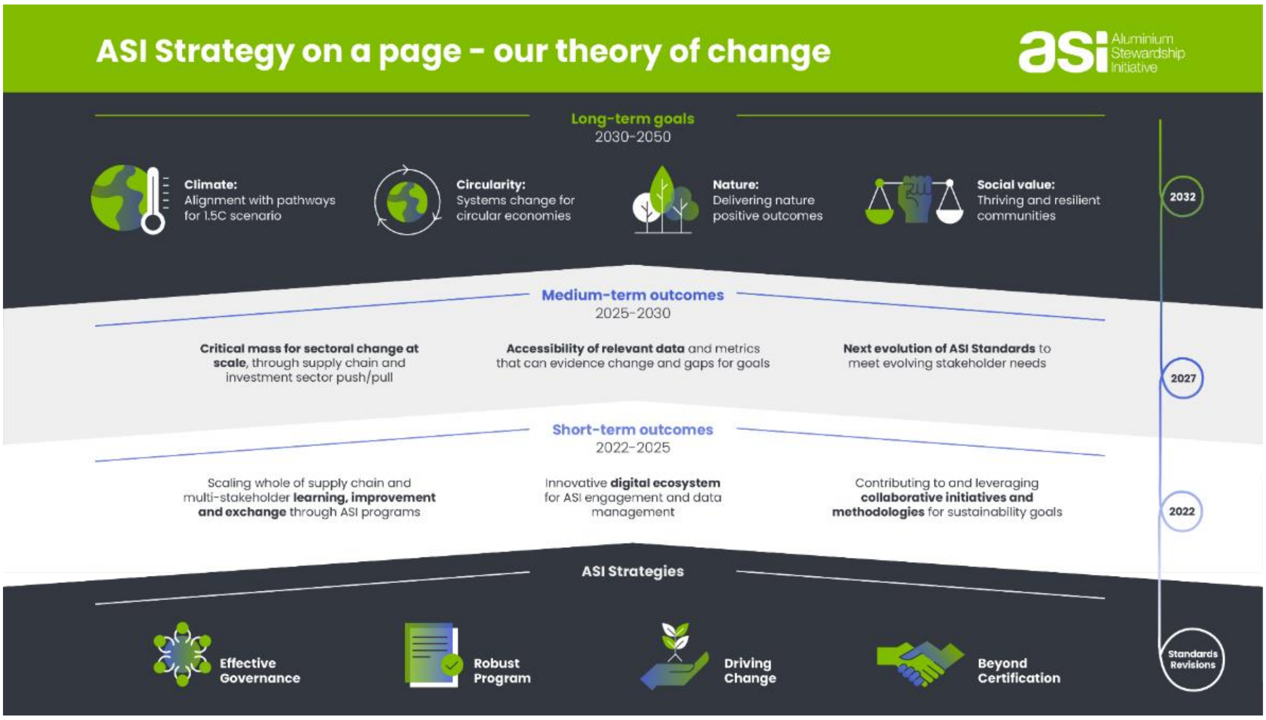


Figure 15 - ASI Strategy plan. (Aluminium Stewardship Initiative (ASI), 2023)

This dedication is demonstrated by their participation in the Aluminums Stewardship Initiative (ASI), where factors like respect for human rights, conservation of resources, and employee welfare are all taken into account when evaluating a company's performance and chain of custody. (Speira, 2023). Figure 15 displays a high-level summary of the ASI strategic plan's primary goals.

ASI's vision is "to maximize the contribution of aluminum to a sustainable society, and their mission is to recognize and collaboratively foster responsible production, sourcing and stewardship of aluminum." (Aluminium Stewardship Initiative (ASI), 2023) And their objectives are:

- "To define globally applicable standards for sustainability performance and material chain-of-custody for the aluminum value chain.
- To promote measurable and continual improvements in the key environmental, social and governance impacts of aluminum production, use and recycling.
- To develop a credible assurance and certification system that both mitigates the risks of non-conformity with ASI standards and minimizes barriers to broad scale implementation.
- To become and remain a globally valued organization advancing programs for

sustainability in the aluminum value chain, which is financially self-sustaining and inclusive of stakeholder interests. "
(Aluminium Stewardship Initiative (ASI), 2023).

2.3 HOT ROLLING PRODUCTS AND ALLOYS

2.3.1. ALLOYS

Since aluminum can be used for a range of different purposes with different requirements, it might be necessary to improve and specialize its properties. This can be done with the intention of improvements in the materials strength, workability, electrical conductivity, or corrosion resistance, for instance. An alloy is a substance created by mixing aluminum with additional elements to change its properties. (Helmenstine, 2019). Depending on the needs and the intended use of the material, an alloy can have a wide range of different compositions. Other advantageous substances are incorporated when the aluminum is liquid. Up to 15% of the mixture may contain additional ingredients in varying amounts. After cooling, the mixture solidifies into a homogeneous solid solution. (Helmenstine, 2019).

"This is a list of some important aluminum or aluminum alloys.

- *AA-8000: used for building wire per the National Electrical Code*
- *Alclad: aluminum sheet made by bonding high-purity aluminum to a high strength core material*
- *Al-Li (lithium, sometimes mercury)*
- *Alnico (aluminum, nickel, copper)*
- *Birmabright (aluminum, magnesium)*
- *Duralumin (copper, aluminum)*
- *Hindalium (aluminum, magnesium, manganese, silicon)*
- *Magnalium (5% magnesium)*
- *Magnox (magnesium oxide, aluminum)*
- *Nambe (aluminum plus seven other unspecified metals)*
- *Silumin (aluminum, silicon)*
- *Titanal (aluminum, zinc, magnesium, copper, zirconium)*

- *Zamak (zinc, aluminum, magnesium, copper)*
- *Aluminum forms other complex alloys with magnesium, manganese, and platinum. "*

(Helmenstine, 2019).

The common names of the alloys are represented by a four-digit number, where the first digit denotes the series or class.

1xxx - Series 1xxx represents alloys are made of 99 percent or higher purity aluminum. (Helmenstine, 2019).

2xxx - Copper is the main component of the aluminum alloy represented by the 2xxx series. These alloys gain strength through heat treatment. These alloys are not as corrosion resistant as other aluminum alloys and may need be painted or coated before use. 2024 is the most popular alloy used in aircraft. (Helmenstine, 2019).

3xxx - Manganese with a small amount of magnesium are the main component of the aluminum alloy represented by the 3xxx series. This series' most popular alloy, 3003, is workable and moderately strong. Cooking utensils are produced using 3003. One of the alloys used to create aluminum beverage cans is alloy 3004. (Helmenstine, 2019).

4xxx - Silicon is the main component of the aluminum alloy represented by the 4xxx series. As a result, the metal's melting point decreases without making it brittle. Wire for welding is produced using this series. To create filler alloys for welding automobiles and structural components, alloy 4043 is used. (Helmenstine, 2019).

5xxx – Magnesium is the main component of the aluminum alloy represented by the 5xxx series. These alloys are robust, weldable, and resistant to corrosion in the sea. In addition to being used to create the lids for aluminum beverage cans, they are also used to create pressure vessels, storage tanks, and various marine applications. (Helmenstine, 2019).

6xxx - Silicon and magnesium are the main components of the aluminum alloy represented by the 6xxx series. Magnesium silicide is created when the components are combined. These alloys can be heated treated, welded, and formed. They are moderately strong and exhibit good corrosion resistance. This series' most popular alloy, 6061, is used to create truck and boat frames. (Helmenstine, 2019).

7xxx - Zinc are the main component of the aluminum alloy represented by the 7xxx series. The end product is extremely strong and can be heat treated. The important alloys 7050 and 7075 are both used in the manufacture of aircraft. (Helmenstine, 2019).

8xxx - “These are aluminum alloys made with other elements. Examples include 8500, 8510, and 8520.” (Helmenstine, 2019).

Speira has extensive experience with aluminum and rolling of the various aluminum alloys. Due to its high strength and corrosion resistance, the 5083 alloy makes a suitable material choice for ships and offshore constructions. Due to the alloy's high percentage of recycled material, it is a sustainable alloy with a small carbon footprint. The dimensions are modified based on the intended use area, and are made with widths of up to 25000 mm and thicknesses of up to 12 mm. The material combines high strength, superior weldability, and bending properties.

Speira makes two types of this alloy, which is Standard VIA Maris and an upgraded, strengthened version called VIA Maris Njørdal. In figure 16, the minimum yield strengths and the minimum ultimate tensile strengths are represented for the diverse types of 5083 aluminium alloys. (Speira, 2022). The highest upgraded alloy version, Njørdal H116, can achieve minimum yield strengths of 220 MPa and minimum ultimate tensile strengths of 305 MPa.

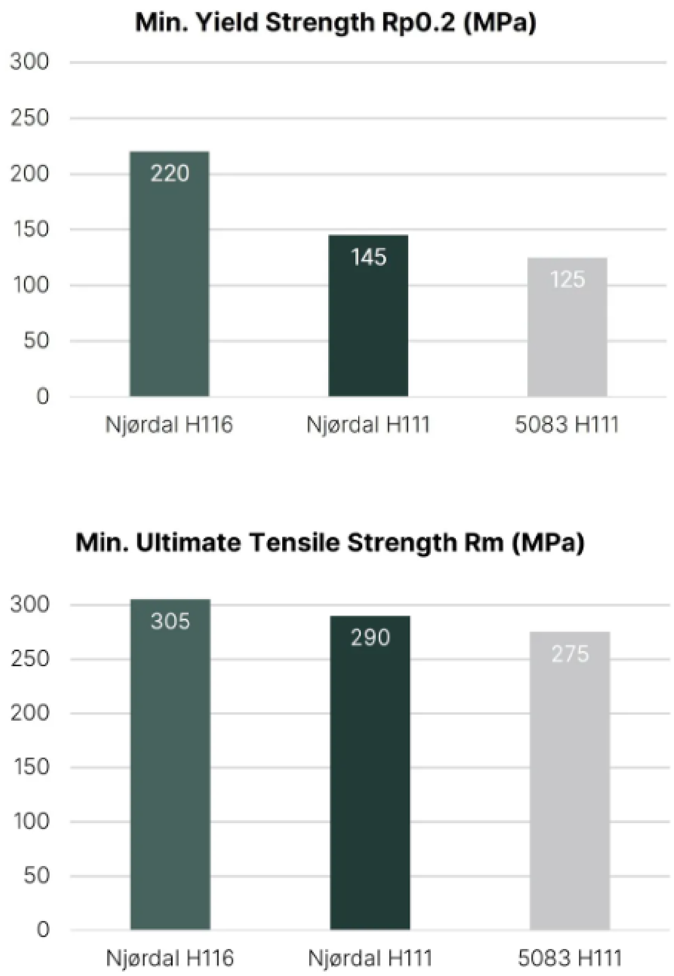


Figure 16 - Comparison of strength between the different types of 5083 alloys. (Speira, 2022)

Table 1 - VIA Maris Njørdal H116, material data sheet. (Aluminium solutions for shipbuilding, 2022).

Material data sheet

Speira designation: **VIA Maris Njørdal H116**
DIN EN 485-2 & 573-3 designation: **EN AW 5083 – AlMg4.5Mn0.7**
Semi-finished product: **Coil, sheet & plate, tempered (H116)**
Thickness: **3.0 - 8.0 mm**

Chemical Composition

(in weight-%)

Element	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Others each	Others total
Min.				0.40	4.0	0.05				
Max.	0.40	0.40	0.10	1.00	4.9	0.25	0.25	0.15	0.05	0.15

Physical Properties

(typical values)

Density g/cm³	Elastic Modulus (GPa)	Shear Modulus (GPa)	Spec. Heat capacity (J/(gK))	Melting range (°C)	Thermal Conductivity (W cm⁻¹ K⁻¹)					Electrical Conductivity (mΩ⁻¹mm⁻²)
					-200°C	-60°C	+20°C	+100°C	+200°C	
2.66	69.2	25.8	1.03	575-640	0.61	1.06	1.2	1.31	1.4	15-19

Mechanical Properties

(As delivered H116)

Rp0,2 (MPa)		Rm (MPa)		A50 (%)	
Min.	Max.	Min.	Max.	Min.	Typical
220	-	305	-	10	12

Mechanical Properties

(After welding in the weld zone)

Rp0,2 (MPa)		Rm (MPa)		A50 (%)	
Min.	Typical	Min.	Typical	Min.	Typical
145	145 -155	290	300-320	15	18-22

The material data sheet for the common alloy VIA Maris Njørdal H116, which is used in shipbuilding and the marine environment, is shown in table 1. The chemical composition is first listed in a table with the percentage of each element in the alloy shown. The physical characteristics of the alloy, such as elastic and shear modulus and electrical and thermal conductivity, are shown in the second table. As strength can be decreased in the welding zone after welding is complete, the two final tables compare mechanical properties before and after welding.

Figure 17 - Construction of a ship's hull with 5083 alloy. (Speira, 2022).

With their special thermodynamic processing, VIA Maris Standard and VIA Maris Njørdal produce plates which withstand harsh marine environments even without being painted. (Speira, 2022) Figure 17 shows the construction of a ship hull made of aluminum. The welding process creates a complete and sturdy construction out of the aluminum components.

2.3.2 MELTING AND CASTING PROCESS

The addition of either cold metal, liquid aluminum, or both is melted in the melting furnace. Gas heaters are used to heat the melting furnace, which is heated to a temperature of about 700 - 800 degrees. Other elements are additionally added in various amounts to increase the materials strength, depending on its alloy. Each alloy has a specific mixture, so the mixture depends on the specific alloy that is being created. Impurities are manually skimmed off after the mixture has been fused using equipment on a vehicle that is fed into the furnace and removes slag. Figure 18 illustrates the melting, rolling, and finishing process.

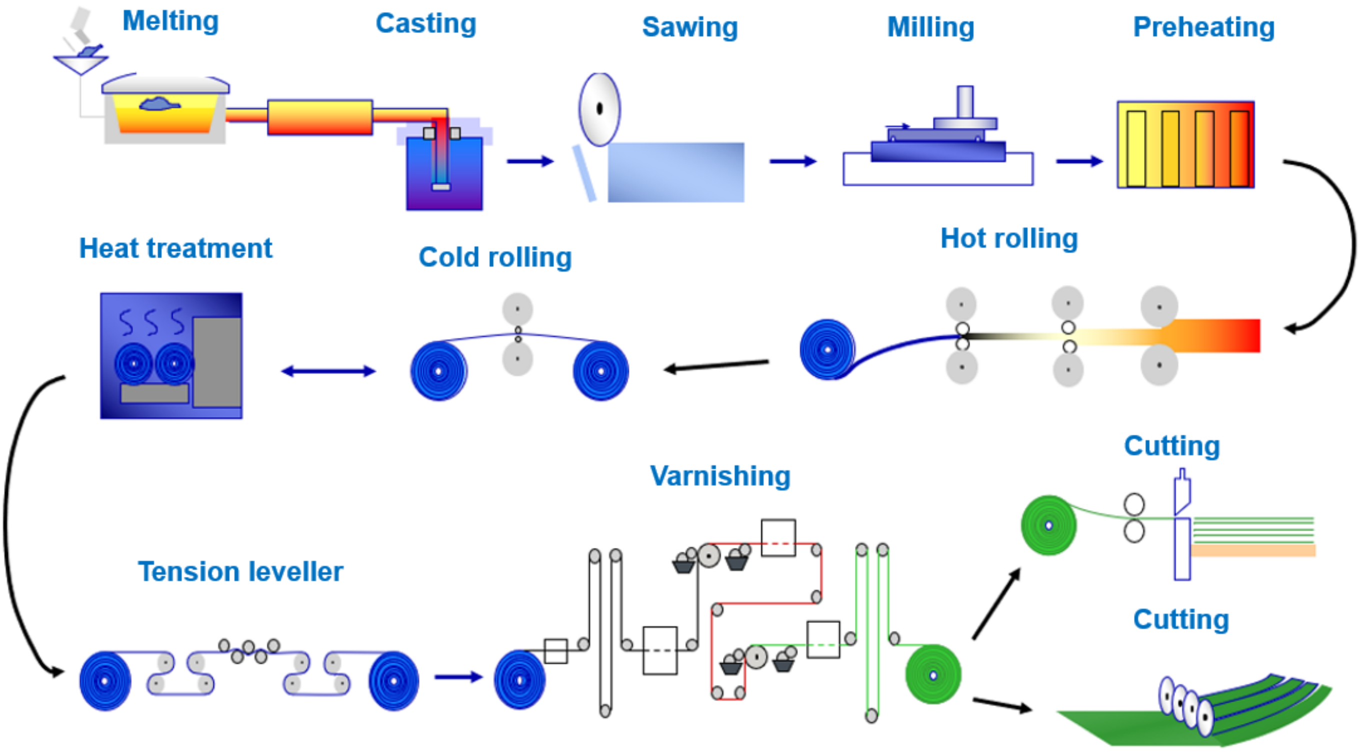


Figure 18 - Melting, Casting and Rolling process. (Brynjulfsen, 2020)

The casting furnace is then fed with the molten mixture. A permanent form, a block, is created here by setting the mixture into a solid form for casting.

Sawing is done for practical purposes in case the block has grown too long or was purposefully cast longer so that it will fit in the oven.

Milling – Before undergoing further processing, the surface created by the casting process must be removed. This is for the benefit of the product as well as the rollers.

Preheating is done for two reasons: First, in order to reduce the thickness as much as possible, the block needs to be heated. The metal becomes suitable for further processing after the casting structure has been "cleaned up" by the temperature.

The block is rolled into a different format by using hot rolling. This is required to continue with the cold rolling process. The item transforms from a block to a soft coil. Cold rolling is done to change the thickness and increase the strength. The more you roll, the harder the metal becomes. The heat treatment changes the metal's softness but not its thickness. The metal gets softer the more you anneal it. A clever combination of rolling and annealing will make it possible to produce products with the required thickness and strength for the intended use.

The final product's surface quality is impacted by the milling depth. Preheating time and temperature have an impact on the location of alloying elements in the metal, which can have an impact on the results of cold rolling and annealing. The coil's profile during hot rolling may have an impact on the final product. The final product's degree of cold deformation (hardness) is influenced by the hot roll's thickness. The impact of cold rolling is influenced by the cooling time between hot and cold rolling.

2.3.3 ROLLING ALUMINIUM

The deformation of metal occurs during rolling. Deformation occurs in-between rolls and can be accomplished using either hot rolling or cold rolling. The metal is drawn into the gap between the rolls by frictional forces, which causes the material to be compressed and thinned out. Due to the action of the rolls compressing the work piece, the cross-sectional area is reduced, and the length is increased. (SlideShare, 2022).

Figure 19 and 20 illustrates the different principle with hot and cold rolling, respectively, where in hot rolling, the metal is rolled back and forth both ways, while cold rolling it is only rolled one single way.

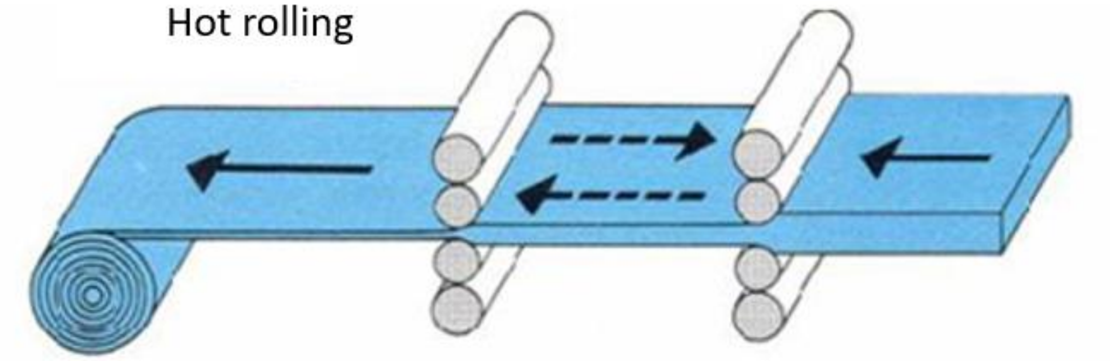


Figure 19 - The principle of hot rolling. (Industriskolen, 2018)

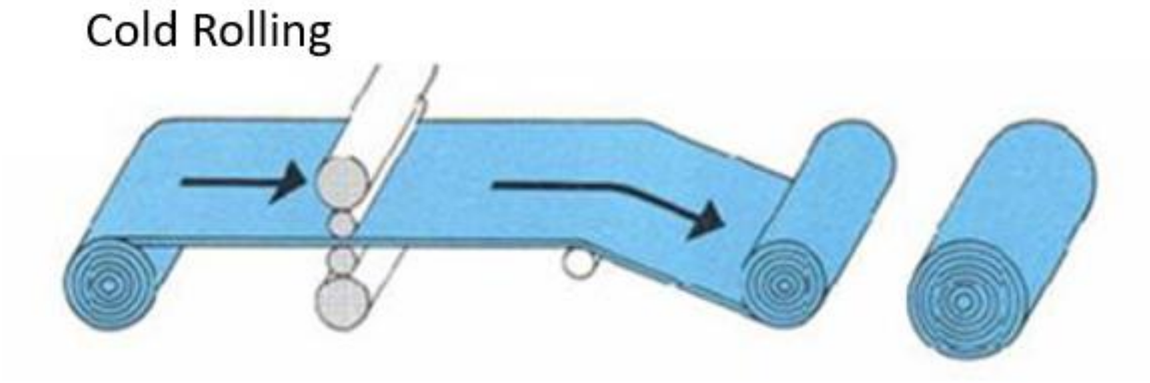


Figure 20 - The principle of cold rolling. (Industriskolen, 2018)

Hot rolling, as illustrated in figure 21, is typically used to break down ingots into blooms and billets for the first time. Hot rolling is then used to create plate, sheet, rod, bar, pipe, and rail. (SlideShare, 2022). The goal with rolling is to increase length while maintaining a constant width while reducing metal thickness. The material in the sheet's center is constrained in the sheet's width's z direction, and the sheets' undeformed shoulders of material on either side of the rolls prevent the sheet's extension in the width direction. In that matter, the material grows longer rather than wider under this circumstance, which is referred to as plane strain. (SlideShare, 2022, s. 35/107).

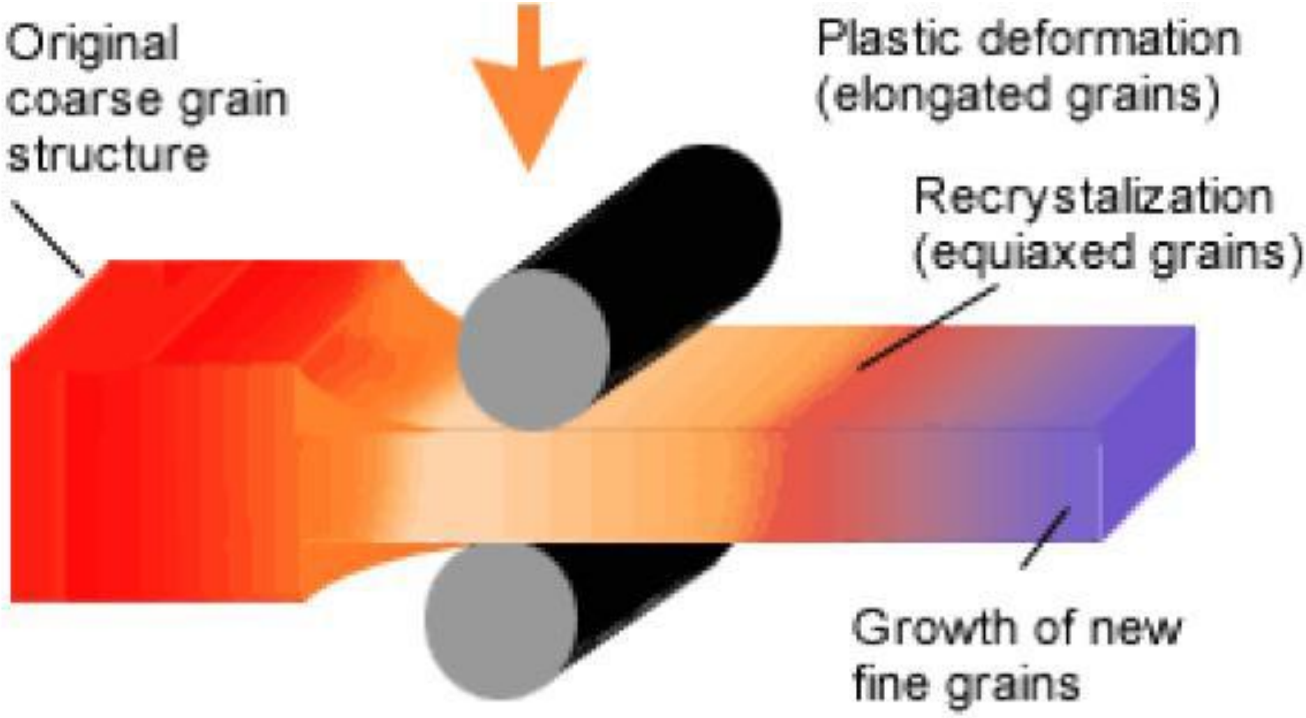


Figure 21 – Rolling ingot. (SlideShare, 2022)

After a 5083-alloy ingot has been created, the product is rolled into the desired shape using hot rolling. For hot rolling, the process is conducted above the recrystallisation temperature. The pressure applied is less than with cold rolling, due to the high temperature. The coarse grain becomes fine grain, and no residual stresses are created. Compared to cold rolling, hot rolling improves ductility while reducing surface finish and accuracy. (SlideShare, 2022).

The region of the metal that has a continuous orientation of a crystal lattice is known as the grain structure. The structure is made up of a variety of grains that are arranged in different directions and encircled by grain boundaries. The high temperature during hot rolling of the metal alters the grain structure. (Onu, Ikumapaya, Akinlabi, & Olatunji, 2020). The crystals elongate in the direction of rolling; in hot-rolled crystals, they reform after passing through the deformation zone. The strip's penetration depth into the deformation zone is both shortened and increased. The grain structure of the cast is altered by hot rolling into a toiled grain structure, which causes the cast to have an uneven grain structure and extend in the direction of solidification. (Onu, Ikumapaya, Akinlabi, & Olatunji, 2020, p. 4/7).

According to Samarasekera, hot rolling causes the mechanical characteristics and microstructure of the material to change, which results in the elongation of the structure's grain length. The material's stress during roll passage causes an increase in the dislocation density and work hardening to take place. An increase in internal energy causes the dynamic and static mechanisms to become more malleable during the process. (Samarasekera, 2003).

"Dynamic microstructural phenomena are those that occur during deformation, whereas static phenomena are those that take place in between passes. While dynamic and static recovery and static recrystallization are the main softening mechanisms in aluminum alloys, static recovery and dynamic and static recrystallization are the main mechanisms in the austenite phase. As opposed to recrystallization, which involves the nucleation of new, strain-free grains at grain boundaries, recovery is characterized by a minimal amount of softening." (Samarasekera, 2003)

Figure 22 depicts the modifications made to the metal's grain structure during hot rolling. The hot rolling process successfully reduces grain size while also transforming non-uniform grain ingot into uniform grains and resulting in significant improvements in ductility and strength. An equiaxed grain structure is still maintained after the average grains have been reduced by hot rolling, which is done above the recrystallization temperature. (Onu, Ikumapaya, Akinlabi, & Olatunji, 2020)

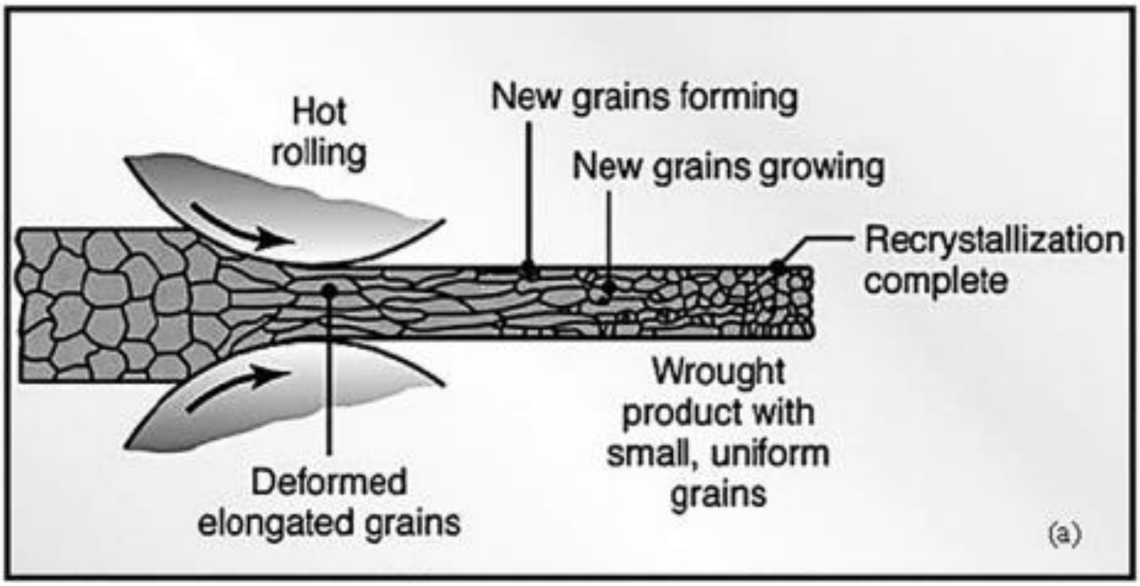


Figure 22 - Changes in the materials microstructure during hot rolling. (Onu, Ikumapaya, Akinlabi, & Olatunji, 2020)

Size and thickness of the plates created for the vessel are determined by the vessels design, its strength calculations, and execution process. The plates are then delivered to the production area where the hull will be made.

The process of extrusion allows for the creation of profiles in a wide variety of shapes from aluminum. Extrusion improves strength and stiffness while also making the fabrication assembly simpler. (LEADRP, 2023). Due to its high malleability, aluminum has the benefit of being simple to extrude into a desired shape. (SlideShare, 2022, s. 40/107). In consideration of malleability and compared to steel, extrusion would be more difficult to accomplish, therefore time can be saved when building a hull out of aluminum.

By rolling the metal sheet to a specific shape using a number of forming rollers in a continuous method, a variety of sections can be produced, some illustrated in figure 23. (SlideShare, 2022, s. 40/107).

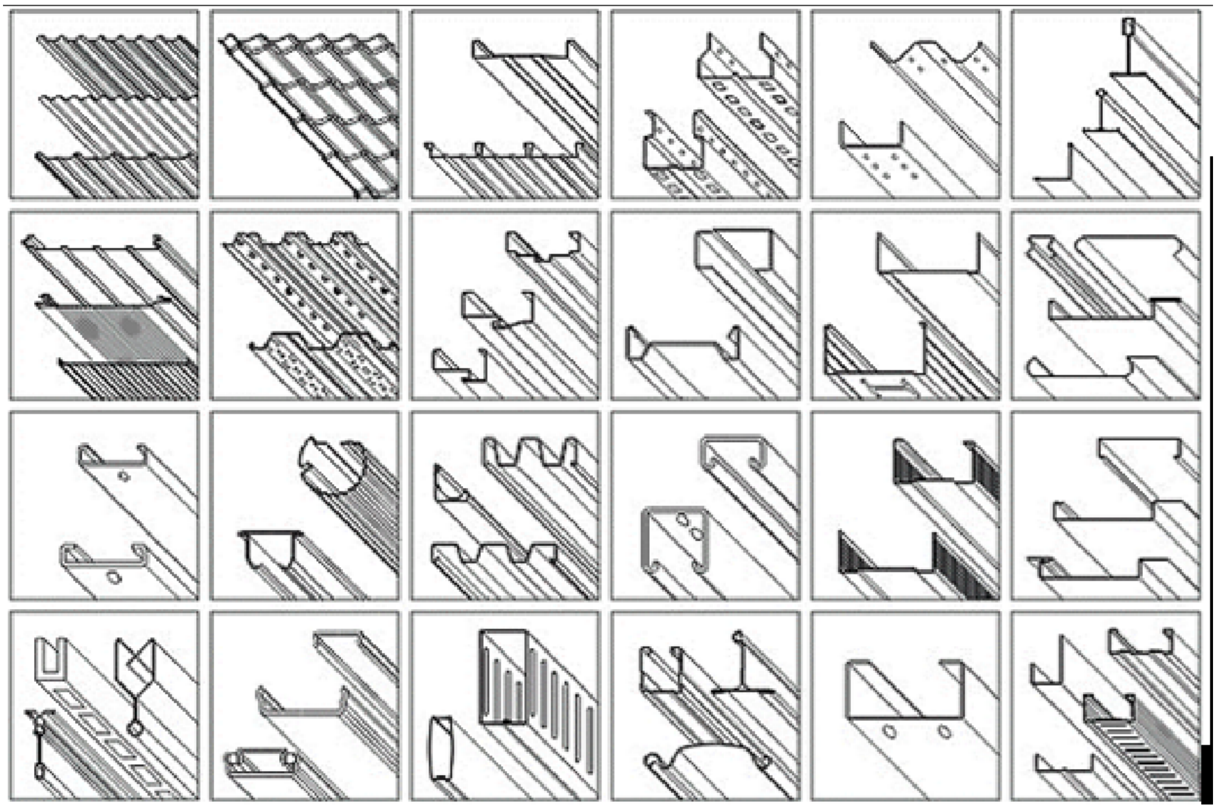


Figure 23 – Different shapes of extruded aluminium. (SlideShare, 2022, s. 40/107)

CHAPTER 3. THE ALUMINUM HULL

3.1 WHY ALUMINIUM?

When used properly, aluminum is a suitable material choice for a maritime environment and can offer significant practical and financial advantages. Seawater-resistant aluminum structures typically weigh half as much as equivalent steel structures of the same capacity, and the structures are then equal in strength by adjusting for variations in the material properties. (MBHydraulikk AS, u.d.). Since winches and cranes are frequently located high up in vessels, their placement has a significant impact on stability, which can be compensated with extra ballast. Because less ballast is required, the weight savings from using aluminum will be able to reduce fuel consumption while also reducing vessel weight and increase load capacity. (MBHydraulikk AS, u.d.).

In contrast to steel, which can become brittle and vulnerable in extreme cold, aluminum will perform better when the temperature drops, making it a good choice for use in cold and arctic regions. Therefore, arctic-operational structures should be built out of seawater-resistant aluminum if they are to be fully loaded in all climatic conditions. (MBHydraulikk AS, u.d.).

According to SOLAS (Safety of life at Sea) regulations to fire classification, aluminium, like steel, is an approved construction material. Normally, aluminum will not produce any heat or gases that could fuel a fire. (Hydro Aluminium, 2001, p. 70/84). The use of aluminum at high temperatures must be considered. When the temperature rises above 100 degrees, this can lead to significant changes in the mechanical properties, especially when it has been heat-hardened or cold-worked. In general, elongation at break increases as temperature rises, while impact strength and tensile strength decrease. The type of alloy, temperature, and time scale all affect the changes. It is reasonable to assume that properties like compressive, shear, and fatigue strength vary in direct proportion to tensile strength. (HYDAL ALUMINIUM PROFILER, u.d.). Aluminum does not burn, and melts at temperatures above 500 degrees. (Iversen, 05).

There are specifications for steel and aluminum structures that must be followed in order to prevent fires; approved non-combustible materials must be used as insulation in order to keep the temperature from rising above 139 degrees above the initial temperature of the exposed surface. Additionally, this is to guarantee that the temperature of the remaining surface, including joints, does not rise by more than 180 C from the initial temperature. (Alcan Marine, 2021, s. 5/10).

"Synthetic vitreous fibers (of silicates) of random orientation, whose percentage by weight of alkaline oxides and alkaline-earth oxides (Na_2O + K_2O + MgO + BaO) exceeds 18%" are the thermal insulation materials used in aluminum structures, such as hulls. When compared to the commonly used insulation material "rockwool," the insulation is non-toxic, much thinner, and can reduce weight by about 40%. (Alcan Marine, 2021).

Low temperatures on the other hand will result in an increase in the mechanical properties. Contrary to the majority of steel types, aluminum does not become brittle. The fase centered cubic structure of aluminum causes it to exhibit a remarkable increase in elongation and tensile strength all the way down to -200 degrees. (Johansen, 2012) (Kallestad). The material becomes tougher, resulting in an increase in strength. For applications requiring low temperatures, such as LNG tanks, aluminum is an excellent construction material. (Kallestad).

Aluminum is the strongest non-toxic material currently available when comparing the specific weight of the material to other materials. Heat reflectivity on a matt oxidized aluminum surface is 5–10 times greater than on an untreated steel surface (Hydro Aluminium) and its tensile strength is about 45% higher than steel's. (Gyda, u.d.). A medium-sized vessel made of aluminum will be lighter than steel, as well as 37% lighter than wood and 10% lighter than plastic, according to research from the Naval Academy. (Iversen, 05, p. 3/9).

3.2 PRODUCTION OF ALUMINIUM HULL

Welding is used to construct aluminum vessels, like in figure 24. The hull is divided into watertight compartments, usually the forepeak, middle compartment, and engine compartment. (Promek, 2023). The hull and deck are formed by welding together the plates after they have been laid out on marble. Since the 1960s, this construction method has advanced significantly, particularly because of improvements in welding techniques. (Torterat, 2021).

For a number of reasons, welding aluminum is actually quite challenging. The oxide layer that surrounds aluminum is a significant factor. Depending on the alloy, the oxide layer melts first at about 2015°C, but the aluminum itself melts at about 660°C. Welding is impossible if the oxide layer melts in the conventional manner because the aluminum will flow away. As a result, the oxide layer needs to be removed both before and during welding. (NordicSteel, 2023).

When welding with gas, a flux is used to dissolve the oxide layer, and when using covered electrodes, an ingredient in the electrode cover dissolves the oxide layer. When the electrode is made positive, the oxide coating disintegrates. The oxide layer must be mechanically removed by grinding and brushing before welding, regardless of the welding technique used. (NordicSteel, 2023). Another issue that needs to be considered is that steel does not conduct heat as well as aluminum does. Therefore, when welding aluminum as opposed to welding steel, heat should be applied much more quickly in order to melt the base material. Despite having a lower melting point than steel, aluminum requires a lot more heat. TIG or MIG welding (using aluminum wire) are acceptable welding techniques because they offer a good, steady heat supply. (NordicSteel, 2023).

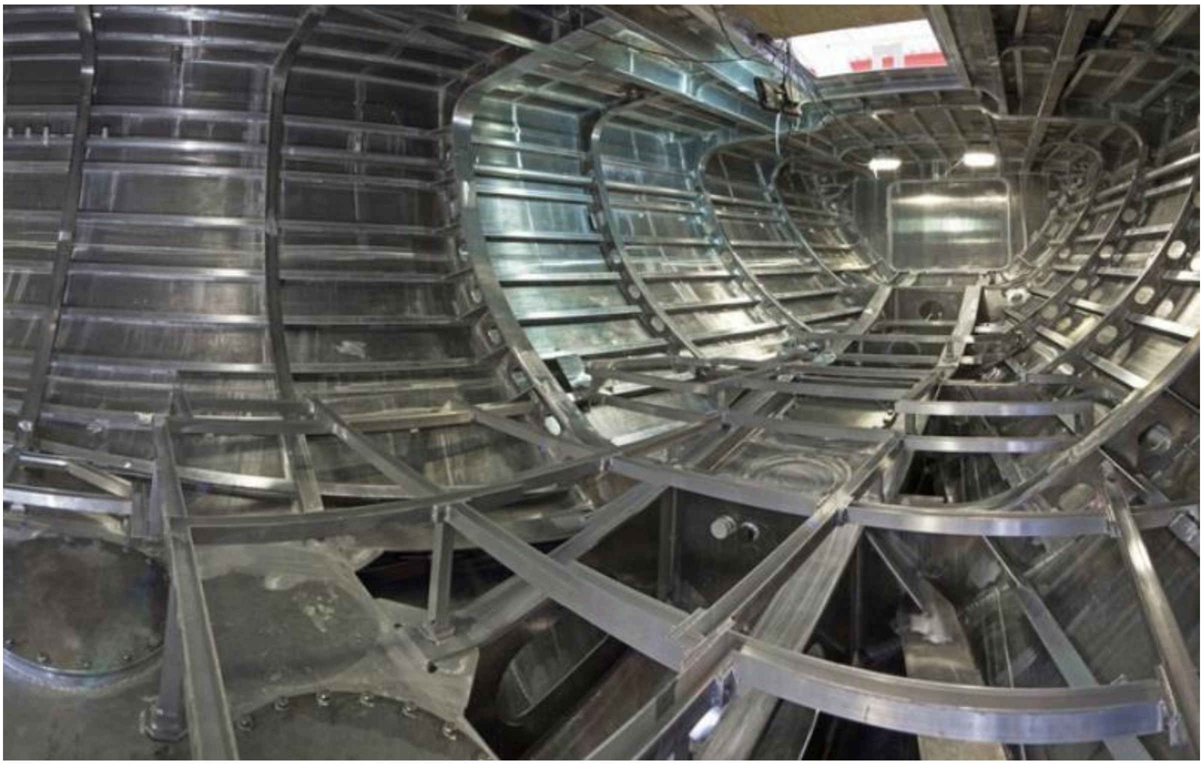


Figure 24 - Production of an aluminium hull. (Myloveiw, 2023)

For welding of the same volume, aluminum and steel require approximately the same amount of heat. Despite weighing a third as much as steel, aluminum conducts heat away four times as quickly. Consequently, when welding, more heat must be added. Aluminum expands about twice as much as steel when heated; conversely, it contracts similarly when cooled. Large shrinking forces frequently occur during welding, which can cause deformations and cracks. This can be avoided by welding as quickly and coldly as possible while using a concentrated heat source. (NordicSteel, 2023).

One-sided welds that are completely burnt through without backing are not possible with aluminum. This is due to the need for a specific thickness of material at the lower edge of the welding joint to prevent melting away while welding. The joints must typically be deeper than the necessary burn-in when one-sided welding. This is so because you have no control over any root issues. (Hydro Aluminium, 2001, p. 47/84). Welds in aluminum should be either double-sided or have backing, with a few exceptions, such as a hollow profile against a hollow profile. Combining the partially burned-through weld with a wedge weld will strengthen the weld when a hollow profile is being welded against a hollow profile. Permanent backing is frequently in the form of an extruded edge detail that stays attached to the structure after welding. This element of the detail follows the profile's longitudinal axis. Usually, there is space built in for the accumulation of impurities. (Hydro Aluminium, 2001, p. 47/84). An aluminum construction's welds may be a deciding factor, but it is uncommon for hidden errors to surface later on, provided that these are tested after the hull is finished. (Iversen, 05).

Aluminum requires junction solutions against other metals, which can be accomplished using a variety of techniques like bolting, gluing, clips, or riveting. Aluminum is connected to other materials and to one another through the use of bolts. Depending on the environment they will be used in, various types of bolts are used. The joint's capacity is determined by the type of bolt chosen and its quality. The most electrochemically negative metal will corrode when different metals are in electrically conductive contact with one another and are submerged in an electrolyte. It is therefore necessary to insulate between the metals for bolted connections in a marine environment to break the contact. (Hydro Aluminium, 2001, p. 53/84).

Compared to steel, aluminum is easier to process, which can reduce costs associated with machinery and equipment purchases. With its many benefits, aluminum is a highly malleable material that is simple to machine, and suitable for casting. Metals can be formed using well-known cold and hot forming techniques. (Hydro Aluminium, 2001, p. 55/84). They frequently need to be braced along the way when bending profiles. If not, there is a chance that pressure-exposed steps and zones will bend sideways, leading to local buckling. (Hydro Aluminium, 2001, p. 56/84).

Aluminum needs to be more insulated than steel because of its lower critical temperature. Fire insulation for steel structures can frequently be placed on the passive side of the fire wall to stop the spread of a fire, whereas fire insulation for aluminum structures must always be placed on the active side of a fire. As a result, there are additional requirements for the fire-protective materials that must be used in aluminum constructions. (Hydro Aluminium, p. 56/81)

For aluminum hulls, like steel, little bracing in the form of load-bearing inner walls, bulkheads, and beams is required. To achieve the same rigidity in the hull, aluminum plates must be slightly thicker than steel plates. When comparing aluminum to steel of equivalent thickness, the former has a 29% higher resistance to buckling and a 12.5% higher resistance to cracking. Compared to steel and aluminum, plastic is performing noticeably worse. (Iversen, 05).

3.3 VESSEL (HULL) IN OPERATION

A vessel with an aluminum hull can be in operation for many decades, and with the requirement of minimal maintenance. (Iversen, 05). A vessel with an aluminium hull in operation is seen in figure 25. Aluminum does not have an odor, doesn't rust, doesn't soak up water, doesn't burn, and doesn't release any gases. Although purchasing aluminum is more expensive than purchasing steel (the price of steel is approximately NOK 16/per kg (Checkatrade, 2022), while the price of aluminum is approximately NOK 27/per kg (Jagdish Metal, 2023)) maintaining aluminum is significantly less expensive, particularly if the vessel is kept unpainted and unvarnished. Seawater-repellent aluminum oxidizes and develops a drab, gray film on the outside of the metal. By preventing further corrosion, this oxidation shields the aluminum. (Gyda, u.d.). A number of factors should be taken into account when operating in a maritime environment, including the necessity of taking precautions against corrosion.

Figure 25 - Vessel with aluminium hull in operation. (Offshore Wind, 2023)

Corrosion is the term used to describe the disintegration or removal of metal that occurs as a result of contact with other substances such as air, water, chemicals, etc. Examples of this include the development of rust on the frame, pitting, weathering of zinc in air and water, and dissolution in acids and alkaline substances. (Kallestad). Corrosion attack is influenced by the nature or characteristics of the substances that come into contact with the metal. The substances or environments that a metal interacts with or is exposed to determine whether or how much corrosion resistance it has. (Kallestad).

Clean air, which is defined as air that has not been contaminated by industrial activity such as the burning of fossil fuels, strong volcanic activity, or drops of sea water, has little to no impact on aluminum and the majority of aluminum alloys. (Kallestad). The same holds true for aluminum when it comes into contact with clean water, which is defined as water that only has negligible amounts of dissolved materials like salts, acids, basic materials, metal ions, etc. (Kallestad). On the other hand, aluminum corrodes in seawater to some extent, but much less than steel as an example. The type and quantity of pollutants and additional soluble substances affect how quickly aluminum corrodes in polluted air and water that contains salts, acids, bases, etc. (Kallestad). It has been established that a lot of aluminum alloys corrode in air and most types of water, but on a much smaller scale than steel. But even relatively small amounts of dissolved copper in water can significantly increase aluminum corrosion. (Kallestad).

An electric current will flow between two different metals connected in seawater or another electrically conductive liquid, creating an electric voltage. Each metal has a unique voltage that can be measured and rated. One metal gain a positive charge in comparison to the other metal as a result of the electrical voltage. (Berge, 2011). The most active metal will transfer its electrons to the noblest during this reaction. Consider the relationship between steel and aluminum as an example. Steel is the most noble metal in this case, and aluminum will function as the anode that sacrifices and disintegrates. Galvanic corrosion is the name given to this quick process. (Berge, 2011).

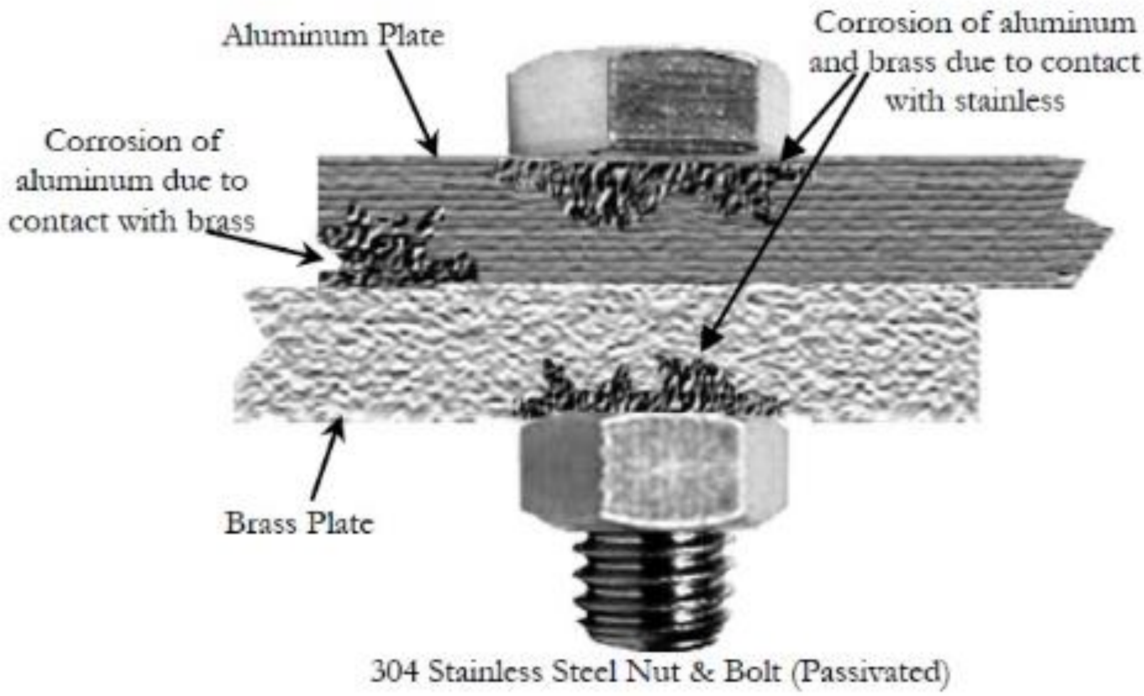


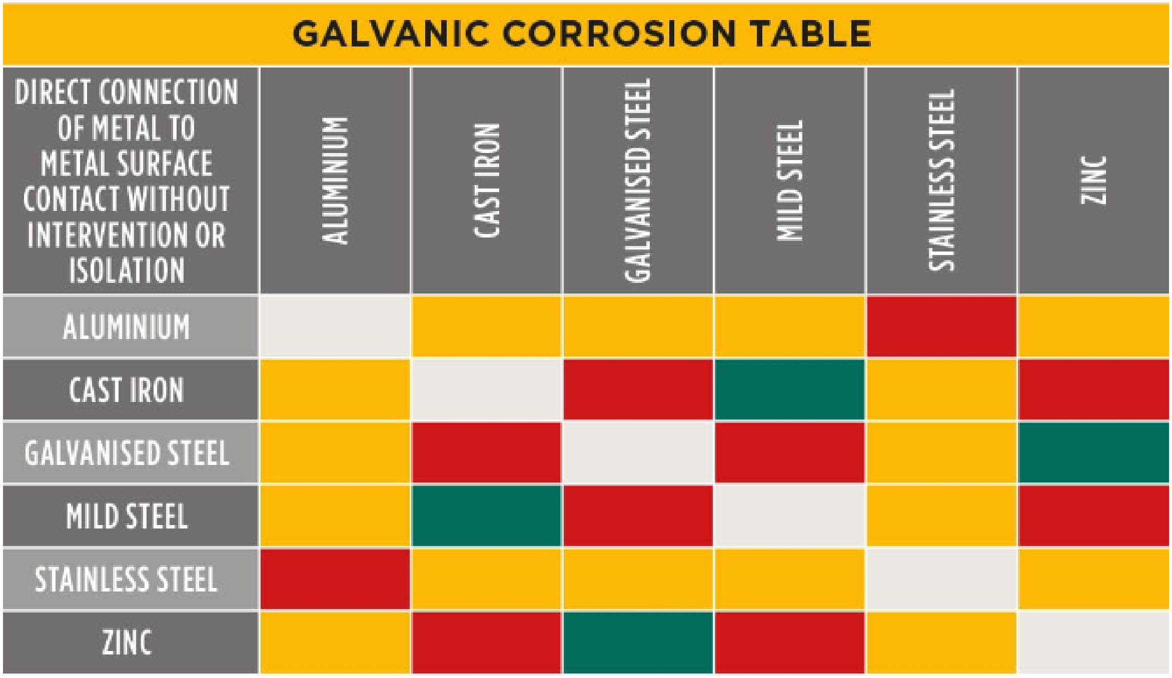
Figure 26 - Galvanic corrosion between steel, aluminium, and brass. (FASTENAL, 2023).

As an illustration, figure 26 depicts the connection of steel, aluminum, and brass. Brass and aluminum will corrode because they are much more anodic and inferior to steel. In this situation, aluminum will corrode even more severely than brass because aluminum is more anodic to steel than brass is. Aluminum will also corrode when it comes in contact with brass because it is more noble than aluminum. To prevent corrosion, it is crucial to consider and account for the voltage range of metals during construction. (FASTENAL, 2023).

A table of the different metals' compatibilities is shown in table 3. An explanation of the significance of the diverse colors in the table is shown in table 2. Simply put, a weak color promotes better compatibility, and a strong color degrades the metals' mach. When steel and aluminum are combined, the color is red, which indicates that galvanic corrosion will take place. This is a bad combination.

Table 2 - Galvanic corrosion indicator. (CPM, 2023).

Table 3 - Galvanic corrosion table. (CPM, 2023).



Pitting corrosion is a term for when aluminum is exposed to corrosion attack in air and water, and it is characterized by the attack being concentrated at certain points or at limited smaller areas of the surface. (Kallestad). Alloys with high strength properties, especially those with a high copper content, are more prone to corrosion than aluminum alloys with low strength properties. (Kallestad). Figure 27 illustrates the pitting corrosion process.

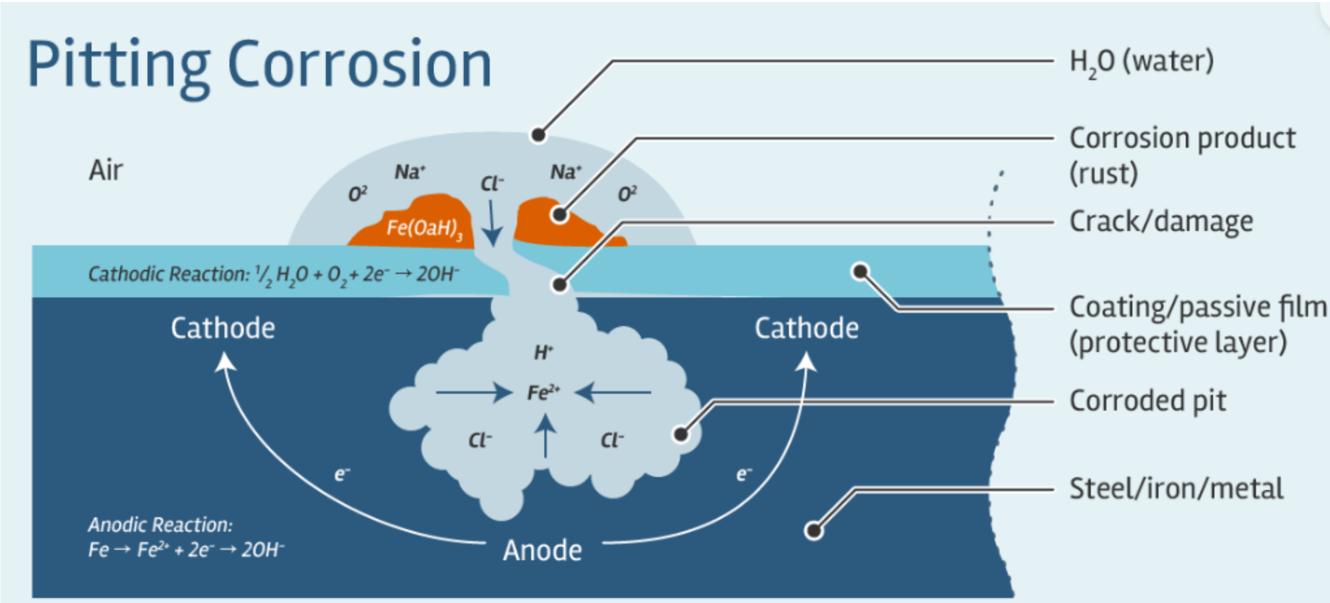


Figure 27 - "Pitting corrosion diagram showing how rust forms in a small anodic area due to the high demand of electrons by the large cathodic area forming a pit below." (D&D Coatings, 2019)

A small pit will develop whenever a cathodic reaction in a larger area (the coating) sustains an anodic reaction in a smaller area (the exposed metal). Oxidation can still take place even in the absence of oxygen. When the small anode is subjected to a large cathode's high electron demand, it results in severe pitting corrosion. With very harmful effects, it will be subtle and happen quickly. While the metal structure below is being damaged, only a small area of rust is visible on the surface. (D&D Coatings, 2019). An example of pitting corrosion is shown in figure 28.

If aluminum is in contact with other metals that have electrical conductivity, corrosion of the aluminum may be significantly accelerated. This is especially true of copper, steel, and lead. On the other hand, contact down with metals like zinc, stainless steel, and others has no negative effects. (Kallestad).

Figure 28 - Example of aluminium corrosion. (Velling, 2020)

The environment and pH level to which aluminum alloys are exposed determine how quickly corrosion evolve. Corrosion resistance is partly determined by the stability of the oxide film layer that forms on top of the aluminum alloy, and corrosion is frequently slowed down over time. The pH values between 4 and 8 are considered stable. In the event that the value falls outside of this range, reactions may take place, with values below 4 dissolving acid and values above 8 dissolving alkalis (which causes rust to form). (Vu, 2023).

The relationship between pH value and aluminum corrosion is depicted in Figure 29's graph. Based on the pH values on the x-axis to which the metal is exposed, the y-axis shows how many millimeters (mm) the aluminum corrodes annually. It becomes obvious that the corrosion is significantly more severe outside of the stable pH value range between 4 and 8.

Corrosion happens when the cathodic and anodic reactions on the metal's surface happen at the same rate. In the case of the anodic reaction, the substance in the environment is reduced, whereas the metal is oxidized in the case of the cathodic reaction. Both oxidation and reduction take place simultaneously thanks to the transfer of electrons between the anode and the cathode. (Vu, 2023).

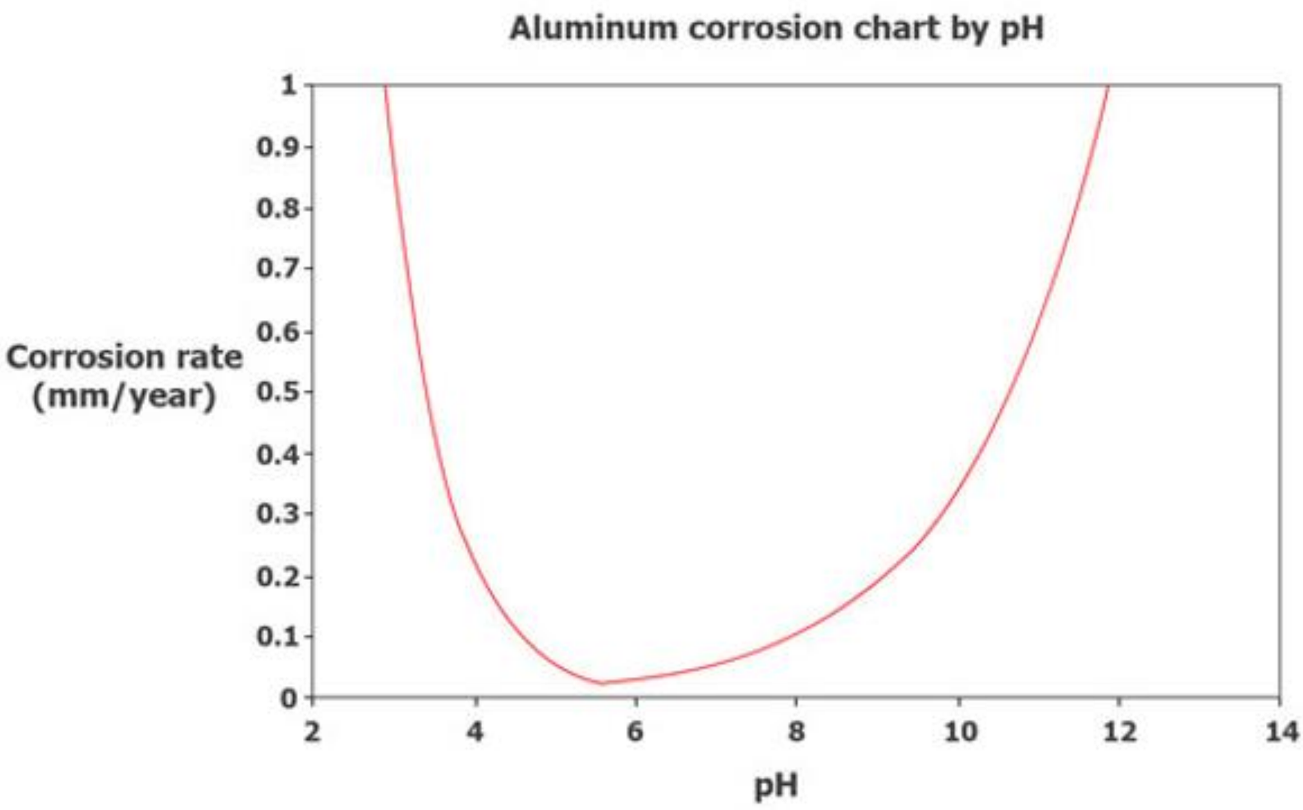


Figure 29 - Aluminium corrosion by pH values. (Vu, 2023)

“These equations explain how electricity travels through metal;

- **Oxidation reaction**: $Al \rightarrow Al^{3+} + 3e$
- **Hydrogen redox reaction**: $2H + 2e \rightarrow H_2$
- **Or oxygen redox reaction**: $O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$ “ (Vu, 2023).

The microstructure of an alloy, which is created based on the alloy's constituent elements and is established by thermomechanical treatment, is where reactions within the alloy take place. In the microstructure of a pure aluminum alloy, there are no metal positions to which no other element has been added. Since the cathodic reaction will not take place, there will be a low likelihood of corrosion. (Vu, 2023).

In contrast, intermetallic particles that produce precipitates with a diameter of 1 to 300 nm form in aluminum alloys that contain additional elements. These deposits have electrochemical properties, making them areas that are vulnerable to corrosion. (Vu, 2023). The likelihood of spark formation in a real-world collision between rusted steel and aluminum is assumed to be negligible. (Hydro Aluminium)**.**

3.3.1 APPLICATIONS OF ALUMINUM VESSELS

Several businesses within the maritime industry have chosen to use vessels with aluminum hulls, and with the increased attention being paid to climate change and the environment, there is now more emphasis on evaluating the material's overall environmental impact. Aluminum, like the marine alloy 5083, is an interesting alternative because it has many benefits at sea.

With today's increasing focus on renewable energy and with larger ongoing and upcoming investments in wind turbines and wind farms, the need for vessels that can be used to support these wind farms at sea has increased. The wind farms will require follow-up, maintenance, and repair, several of them are being made in aluminium, which is an interesting choice as a hull construction material for these purposes. (Aluminium Marine Consultants, 2019-2022). Such as the company Aluminum Marine Consultants, are boat builders for wind farm support vessels (WFSVS), crew transfer vessels (CTV), and service technician work boats.

Figure 30 - Wind turbine transfer vessel. (Aluminium Marine Consultants, 2019-2022).

About 80 aluminum vessels, including the wind turbine transfer vessel shown in figure 30, have been produced so far for this industry. (Aluminium Marine Consultants, 2019-2022). These vessels are specifically created to be able to manage these operations in hazardous weather and climatic conditions. The ships are made of aluminum, which makes for a sturdy construction for boats that will operate wind farms or perform other offshore tasks.

Other maritime industries, such as the fish farm industry, use aluminum vessels as well. Recent investments in aluminum work vessels have been made by the fish farming company Lerøy Aurora in Norway. As the newest addition and a compact workboat for fish farms, “Havørna” (sea eagle) is depicted in figure 31. (Baird Maritime, 2021).

Figure 31 – "Havørna", a fish farm workboat. (Baird Maritime, 2021).

The vessel is specifically built to support operations associated with the farming industry. Additionally, it is designed to be used in a variety of capacities, including search and rescue, diving, ROV support, and other forms of transport. The design pays close attention to maritime safety and is built to withstand the severe weather conditions that the Norwegian aquaculture industry encounters at sea. (Baird Maritime, 2021). The hull of Havørna is made of aluminum to ensure durability and reduce maintenance requirements after regular use in the challenging maritime environments to which the vessel is subjected to.

3.4 HULL MAINTENANCE

Hulls made of aluminum typically require little maintenance. Aluminum is frequently subjected to surface treatment for aesthetic reasons in order to achieve a shiny surface. However, there isn't really any need for surface treatment, with the exception of below the waterline. It is typical to apply primer over a thick, waterproof layer of epoxy-based primer on the hull below the waterline. (YAMARIN cross, 2023).

Surface treatments are used to;

- “Avert marine growth on underwater structures.
- Lower the potential increase in fuel consumption caused by a dirty underwater hull.
- Avoid a matte finish.
- Prevent corrosion pitting during the initial use.
- Conceal the contact surface with other metals that could lead to bimetallic corrosion.
- Prevent the evaporation of the oxide layer.”
  (Hydro Aluminium, 2001, p. 83/84).

Aluminum should never be treated with a copper-based primer, as this causes the aluminum to corrode. Instead, bottom material intended for aluminum should be used. Regular cleaning of the hull will help to keep it nicer, so that maintenance costs also stay low. For the purpose of reducing the increase in fuel consumption, growth and algae must be removed. (YAMARIN cross, 2023).

An important aspect of a boat's maintenance involves sacrificial anodes, as shown in figure 32. Zinc is primarily used as a sacrificial anode, but other metals such as aluminum and magnesium can also be used. In place of the more expensive metal parts of the vessel, such as the shaft, propeller, rudders, stern drive, and other essential components, a sacrificial anode is made of a cheap metal that will corrode. When exposed to water for an extended period of time, the anode's less "noble" metal will corrode first, protecting the metal components from corrosion. (Citimarine, 2022).

Figure 32 - Zink anode. (Citimarine, 2022)

There will be some current flowing between them when two different metals are physically or electrically connected and submerged in water, essentially creating a battery. One of the metals provides the electrons that make up the current by releasing small portions of itself into the seawater in the form of metal ions. (Citimarine, 2022). This will cause the metals submerged to corrode over time. An electrical current is established towards the less noble metal by adding a second, more noble anode. The less noble metal will then receive the current, allowing the anode to sacrifice itself through an ion transfer. (Citimarine, 2022).

To counteract galvanic corrosion, materials that are far away from aluminum in the voltage range and provides electrical insulation can be used. Use of an insulating material with sufficient resistance is necessary to prevent metallic contact between the construction materials. Additionally, care should be taken to prevent liquids from dripping from noble materials and from remaining in spaces between noble materials. (Hydro Aluminium, 2001, p. 82/84).

Electrical systems on board must be created to withstand wet, salty environments in order to prevent leakage current corrosion. Avoiding the use of metal pipes and steel wire may also be beneficial. (Hydro Aluminium, 2001, p. 83/84).

3.5 REPAIR IN CASE OF DAMAGE

Aluminum will flex and bend significantly more than steel in the event of a collision before it fractures. Furthermore, increased strength is provided by the skeleton to which the hull plates are welded, and interior changes are permitted without concern for load-bearing or stiffening bulkheads. (Gyda, u.d.). Impact resistance is a great advantage of aluminum alloy. In the event of a collision, the aluminum hull can recover quickly. Simple weld repairs are all that are needed to smooth out the outer plate if the hull does not leak following the impact. If the hull shell collides and leaks, it just needs to be cut and welded again in accordance with the size of the leak. The advantages of a speedy repair of the aluminum alloy hull are particularly clear, and the quality of the repaired hull is identical to that of the new hull. (Kimple, 2021).

The study “Ultimate strength characteristics of aluminium plates for high-speed vessels,” investigated the maximum strength of a heat-affected zone (HAZ)–equipped, unstiffened aluminum sheet. An idealized HAZ block with a strength knock down factor of 0.67 for 5083-H116 and 0.53 for 6082-T6 has been selected based on DNV guidance. The resulting material stress strain curves are as shown in figure 33. (Benson & Downes, 2011, p. 18/38).

Testing a material specimen under tension or compression reveals how a material responds to stress and strain. When a test specimen is subjected to a gradually increasing axial force, the deflection is measured as the load increases. An illustration of this data would be a load-deflection curve. The elastic modulus of the material and the specimen's geometry (area and length) both affect how much the test object will budge. (MecaniCalc, 2014-2023).

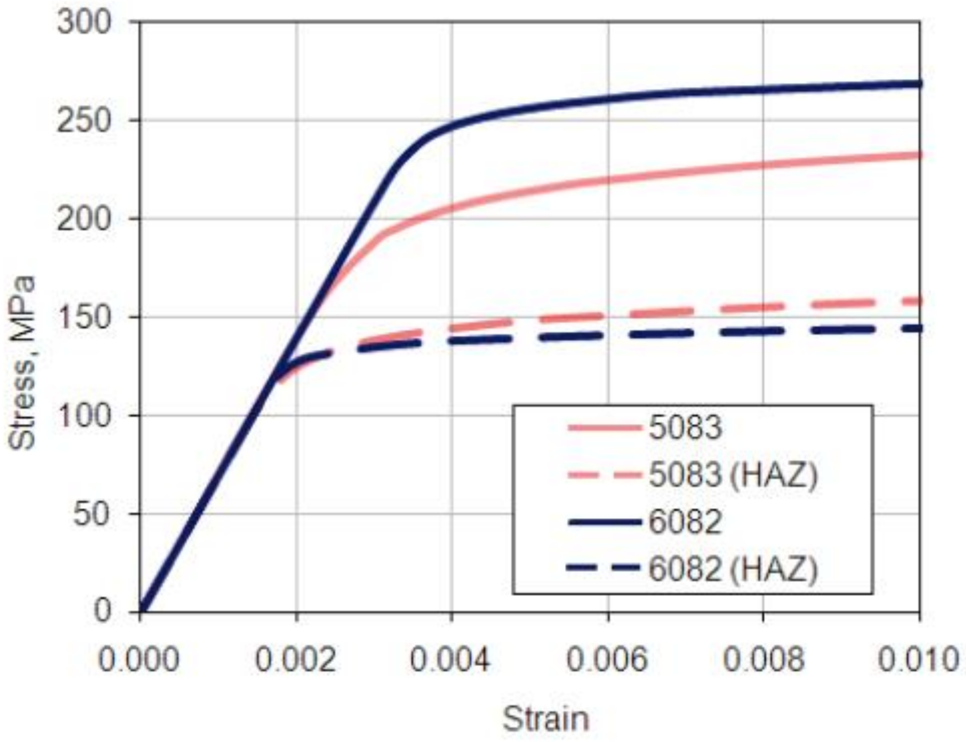


Figure 33 - Material stress strain curves for aluminium alloys 5083-H116 and 6082-T6. (Benson & Downes, 2011)

The elastic modulus of alloys made of aluminum is one-third that of steel. Compared to steel, aluminum alloys typically have a more rounded stress-strain curve. As the yield point for aluminum alloys is typically not identifiable on the stress-strain curve, a 0.2% offset proof stress is taken into account as a substitute for the yield strength. Fig. 34 illustrates the variations in material stress-strain curves between typical ship steel plating and typical marine-grade aluminum alloys. (Khedmati & Hosseinabadi,, 2021).

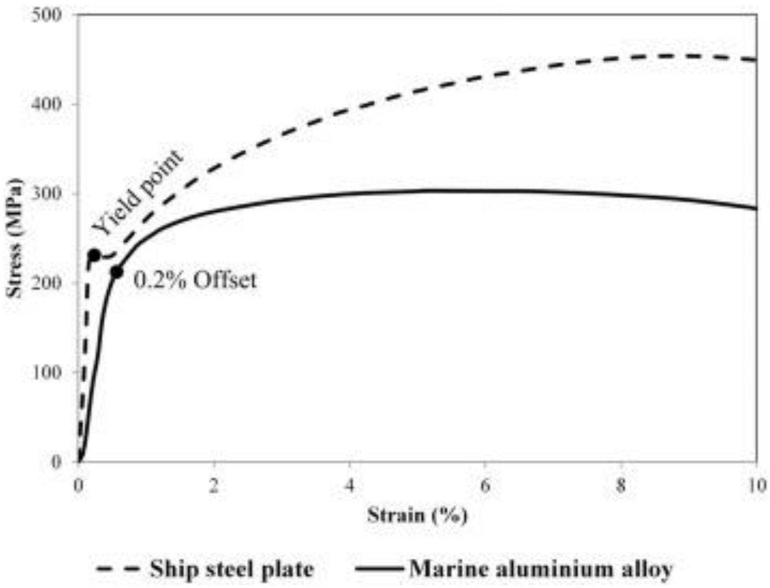


Figure 34 - Stress-strain curve of aluminium compared to steel. (Khedmati & Hosseinabadi,, 2021)

CHAPTER 4. RECYCLING, EMISSIONS AND ENERGY CONSUMPTION

4.1 RECYCLING

There is a need for safe and dependable raw material streams given the unpredictability of the world we live in and the disruption of global supply chains. The value chains for aluminium become more resilient as a result of the increased emphasis on keeping the produced materials and goods in use for as long as possible. This results in a less amount of waste and more resilient value chains. After reaching the end of their useful lives, materials should be recycled as much as possible and then be used to create new products. (Hydro, 2023)**.**

The ability to recycle materials varies depending on the material because some materials are better and easier to recycle than others. Because of its ability to be recycled indefinitely without losing any of its properties, aluminum is known as a permanent material. Aluminum is the product material that is sent to recycling facilities the most often, measured in percentage. As earlier mentioned in this thesis, about 75 % of all the aluminum that has been produced in the world, is still in use today. (UC RUSAL, u.d.). Aluminum recycling requires 95% less energy than producing aluminum from scratch. (Hydro, 2023).

There is a steadily expanding green engagement among material consumers where businesses are focused on lowering their carbon footprint. Post- and pre-consumer recycled aluminum can be separated into two categories. Aluminum that has been used as a product before and for which the carbon footprint has already been taken into account is referred to as post-consumer aluminum. Pre-consumer aluminum is recycled from production waste and hasn't previously been used to make a product. Pre-consumer aluminum has the drawback that the product's emissions have not been taken into account. (Hydro, 2023).

Pre-consumer aluminum is shown on the left side of figure 35 and post-consumer aluminum is shown on the right side.

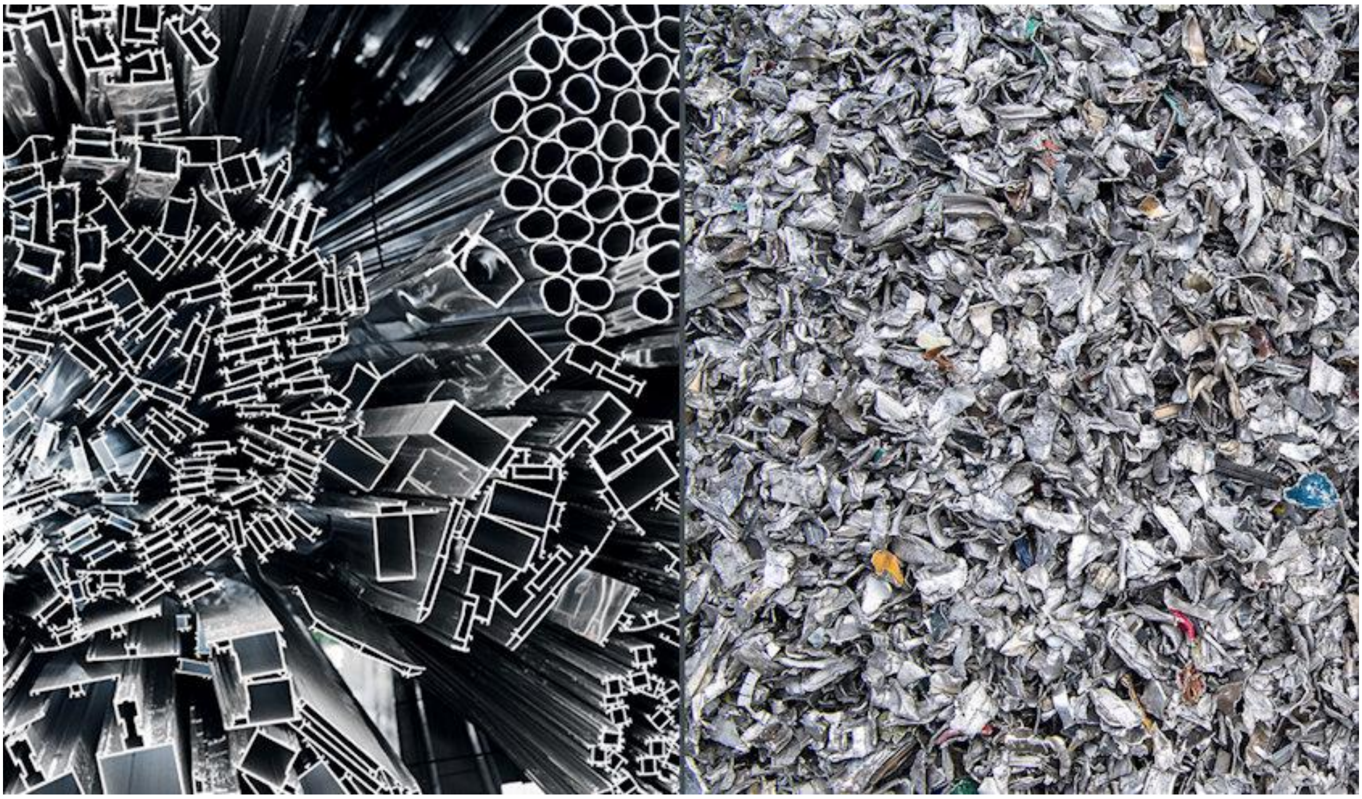


Figure 35 - Recycled aluminium. (Hydro, 2023).

The recycling process is carried out with the following steps, like illustrated in figure 36:

Sorting and shredding - The product (the hull) needs to be taken apart and fragmented. The aluminum then needs to be separated. (Falde, 2018)**.**

Cleaning - In order to get the aluminum pieces ready for melting, the surfaces are scrubbed clean using mechanical and chemical processes. (Falde, 2018)**.**

Byproduct removal - Byproducts are removed in order to purify the molten metal. This can be done mechanically or by using chlorine and nitrogen gas. (Falde, 2018)**.**

Aluminum alloy - In this stage, additives are added to the base metal to create the right alloy. (Falde, 2018)**.**

Compounding - The molten metal is then poured out and shaped into ingots, which can be transported to aluminum processing or manufacturing facilities where new products can be produced. (Falde, 2018)**.**

Figure 36 - Aluminium life cycle, including steps for recycling. (Husband, 2012).

4.2 ECONOMIC PERSPECTIVES

The financial perspective plays a significant and frequently crucial role in shipbuilding. The costs associated with the various material selections must be evaluated, along with the benefits and drawbacks. At the time of writing, the price of steel is approximately NOK 16/per kg or $1,600 per ton (Checkatrade, 2022), while the price of aluminum is approximately NOK 27/per kg or $2,700 per ton (Jagdish Metal, 2023) Aluminum and steel can be compared in terms of price and weight. Given that aluminum is considerably lighter than steel, one can see what a potential compensating factor might be.

The theory for comparing the weights of aluminum and steel is highlighted in a compendium written by Alcan Marine. Three factors can primarily be used to compare it.

- The ratio of mass (M) will be equal to the ratio of density (ρ) for structures with the same thickness (t) that are not exposed to stress. (Alcan Marine, 2023, p. 3/12)
  $\rho_{Aluminium} = 2{,}7\ kg/m^3$
  $\rho_{Steel} = 7{,}8\ kg/m^3$

  $$\frac{M(\text{aluminium})}{M(\text{steel})} = \frac{2{,}7}{7{,}8} = \underline{\underline{0{,}34}}$$

Consequently, only 340 kg of aluminum are required to replace a ton of steel, which results in a 66% saving. (Alcan Marine, 2023)

- Young's modulus ratio is 3 at equal rigidity (E), and the relationship between the ratios of the sheet thicknesses (t) will then be (Alcan Marine, 2023);

$$E(steel) * t^3(steel) = E(aluminium) * t^3(aluminium)$$

$$t(aluminium) = t(steel) * \sqrt[3]{\frac{E(steel)}{E(aluminium)}}$$

$$t(aluminium) = \sqrt[3]{3} * \text{t(steel)}$$

$$\frac{M(aluminium)}{M(steel)} = \frac{2{,}7}{7{,}8} * \sqrt[3]{3} = \underline{\underline{0{,}5}}$$

Therefore, one ton of steel can be replaced with 500 kg of aluminum, saving 50% of the weight.

- The proof stress is 220 MPa for aluminum and 355 MPa for EH36 steel for sheets and non-welded structures, respectively, at equal stress. (Alcan Marine, 2023)

$$\sigma(steel) * t^2(steel) = \sigma(aluminium) * t^2(aluminium)$$

$$t(aluminium) = t(steel) * \sqrt{\frac{\sigma(steel)}{\sigma(aluminium)}} = \underline{\underline{1,65}}$$

$$\frac{M(aluminium)}{M(steel)} = \frac{2,7}{7,8} * 1,65 = \underline{\underline{0,57}}$$

570 kg of aluminum can replace one ton of steel, resulting in a weight savings of 43%. (Alcan Marine, 2023)

Table 4 shows the weight savings that can be achieved by using aluminum rather than steel. Despite being 70 % more expensive than steel, aluminum will be able to make up for some of this cost difference in weight.

Table 4 - Weight reduction for aluminium vs. steel. (Alcan Marine, 2023).

REDUCTION IN WEIGHT OF ALUMINIUM ALLOY STRUCTURES				
Comparison	Criterion	Aluminium	Steel	Potential Saving
Equal thickness	Density	2,7	7,8	66 %
Equal rigidity	Young's modulus	70 000 MPa	210 000 MPa	50 %
Equal stress	Proof stress	215 MPa	355 MPa	43 %

4.3 EMISSIONS AND ENERGY CONSUMPTION

It is crucial to consider the energy consumption in order to evaluate the entire life cycle of aluminum. "*If Norwegian industry is able to use less energy while also maximizing the use of each kilowatt hour, they will save a lot of money and reduce their emissions significantly. The burden on the energy system will be lessened as a result of this value creation for society.*" (Keilman, 2023). Aluminum production requires a significant amount of electricity, and in a typical year, this consumes more than 13% of Norway's total hydropower output. This causes the daily needed energy to produce aluminum to be equal to the annual energy needs of 2,000–3,000 households. (Hovland, 2020)

Hydro aluminum produces aluminium by using hydropower, which requires 12.27 kW/h per kg. An average of 14 kW/h are used to produce one kg of aluminum worldwide. (Hovland, 2020). The energy consumption of Hydro for producing aluminum has significantly decreased, as shown in figure 37. Ongoing efforts are being made to locate effective solutions to reach the future goal, which is 10 kW/h per kg. (Green Car Congress, 2018).

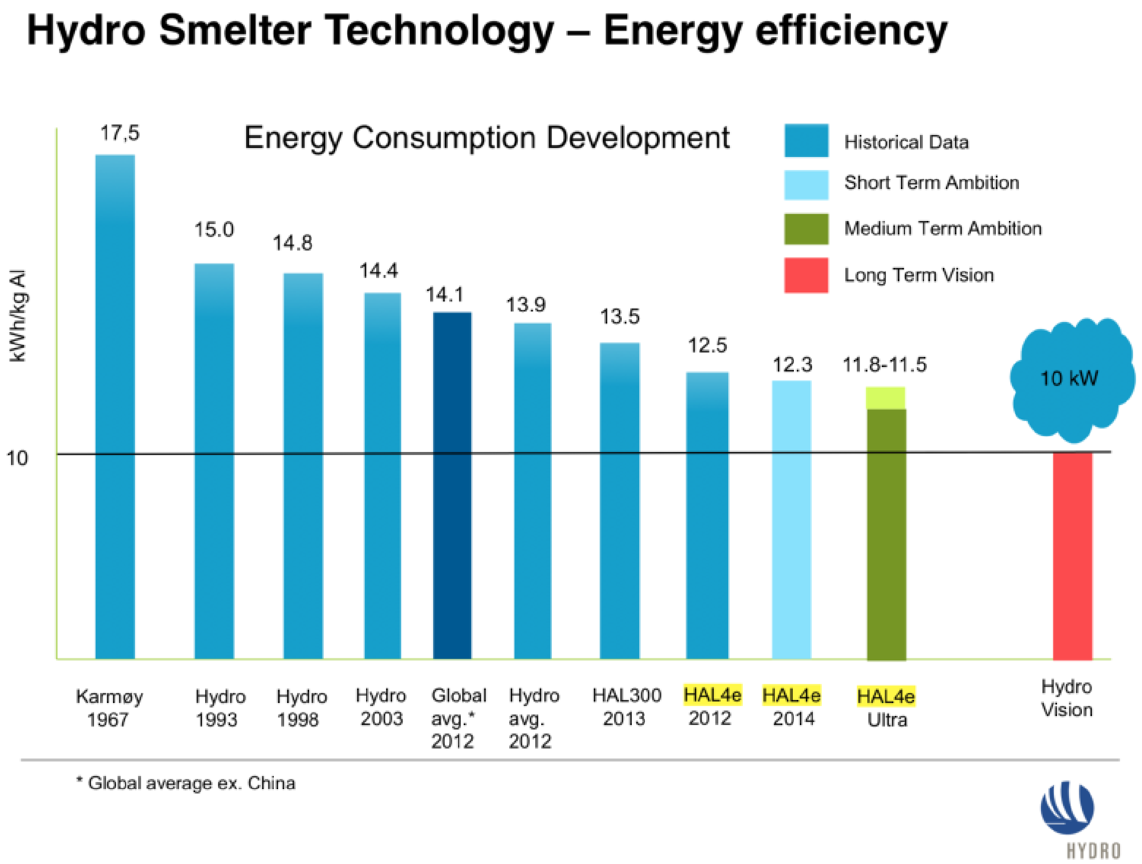


Figure 37 - Energy consumption for aluminium production at Hydro. (Green Car Congress, 2018).

Table 5 shows the energy consumption of the aluminium production process. Aluminium is produced in two stages: primary, from ore, and secondary, from scrap or recycled aluminium, with each stage consuming a different amount of energy.

The biggest energy user is undoubtedly electrolysis. The figure represents the energy consumption on the different stages of aluminium processes, with the unit is gigajoule per tonne (GJ/tonne).

Table 5 - Aluminium energy consumption overview. (Maximpact, 2012-2023).

Process	Thermal [GJ / tonne]	Electricity [GJ / tonne]
Primary aluminium		
Refining of bauxite (Bayer's process) Digesting Calcine kiln	 12.1 6.5	1.4
Carbon anode production	1.0	0.21
Smelting process (Hall-Héroult process)	-	49.0
Secondary aluminium	3 – 9	-
Aluminium processing		
Primary ingot casting	2.8	0.8
Secondary ingot casting	7.2	0.45
Cold rolling	1.0	1.3
Hot rolling	1.3	0.9

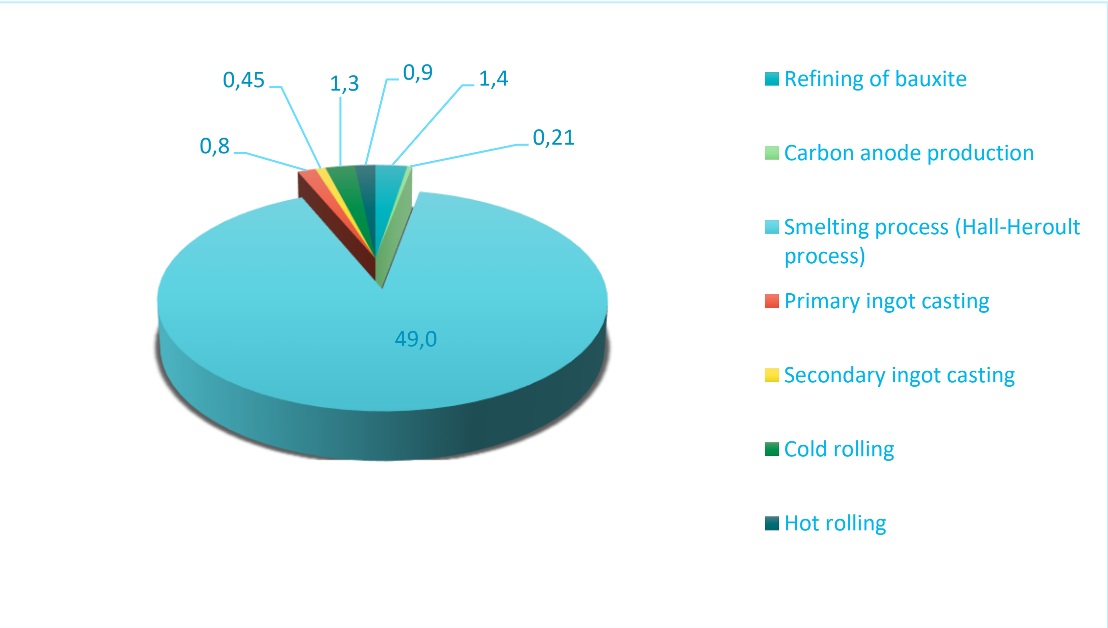


Figure 38 - Energy distribution for primary aluminium.

Figure 38 shows a diagram of energy consumption for aluminium, which shows how the energy percentage required for various processes is distributed differently, as listed in table 5.

In 2020, Norway's aluminum production resulted in nearly two million tons of CO_2 emissions. This represents about 4% of the nation's overall CO_2 emissions. Three-quarters of a CO_2 molecule are simultaneously produced for each metal atom that is created. As a byproduct, this causes 1.5 tons of CO_2 gas to be released for every ton of aluminum. (Senanu, Skybakmoen, & Solheim, 2021).
The aluminum association conducted a study titled "The Environmental Footprint of Semi-Fabricated Aluminum Products in North America," which provides an overview of the carbon footprint per kilogram of aluminum produced, shown in figure 39.

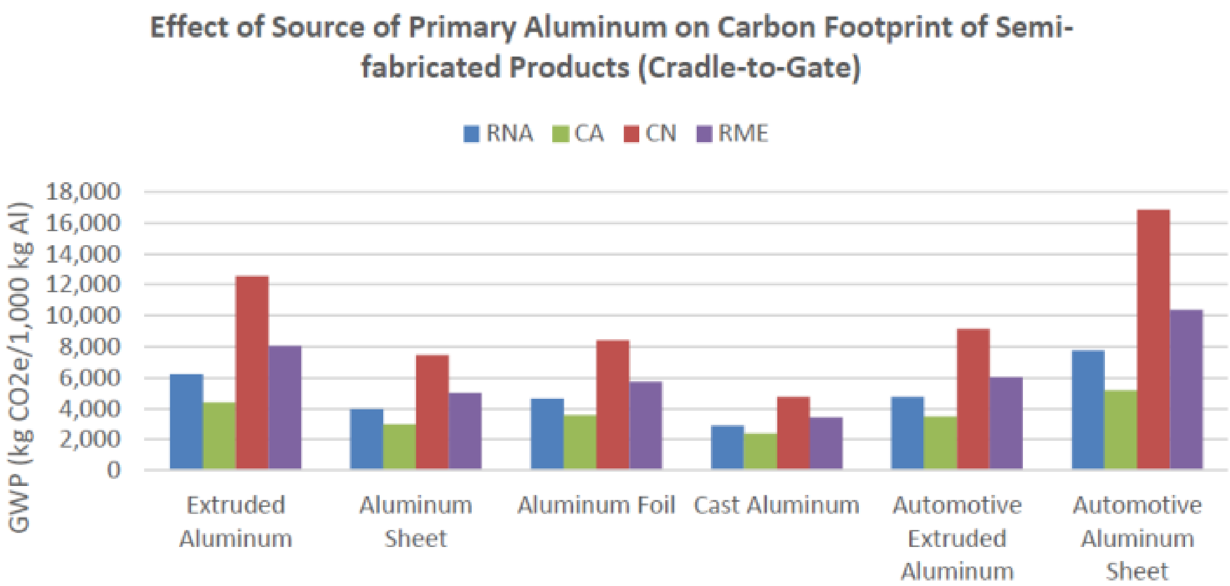


Figure 39 - Carbon footprint from primary aluminium production. (Wang, 2016)

CA stands for Canada, where primary aluminum is only smelted using hydropower electricity. RNA stands for the weighted average of the primary aluminum consumption mix in North America, which is the baseline case. The Middle East is represented by RME, where primary aluminum is mainly smelted with natural gas-fired electricity, while China is represented by CN, where primary aluminum is primarily smelted with coal-fired electricity. (Wang, 2016, p. 8/16). Similar to Canada, Norway also uses hydropower for the production of aluminum. Therefore, it is possible to compare the emission conditions to the emissions reported for CA.

Nunez and Jones conducted the study "Cradle to gate: life cycle impact of primary aluminium production". The various energy sources used for aluminum production in the entire world (GLO) was compared with the rest of the world, excluding China (RoW), and are shown in table 6; Hydropower stands out as being the frequently used energy source for the rest of the world, but when including China (GLO), coal is the most frequently used energy source. (Nunez & Jones, 2015).

Table 6 - Energy sources used for aluminum production. (Nunez & Jones, 2015).

	GLO (GWh)	GLO %	RoW (GWh)	RoW %
Hydro	218,618	41 %	195,980	65 %
Coal	271,643	51 %	67,898	23 %
Oil	389	0 %	389	0 %
Natural gas	26,432	5 %	26,432	9 %
Nuclear	10,997	2 %	10,997	4 %
Total	528,079	100 %	301,696	100 %

As shown in table 7 the "Global greenhouse gas emissions split by unit process and process type and primary energy input (renewable (R) and non-renewable energy (NR)) split by process type" was considered. (Nunez & Jones, 2015).

Table 7 - "Global greenhouse gas emissions split by unit process and process type and primary energy input (renewable (R) and non-renewable energy (NR)) split by process type." (Nunez & Jones, 2015).

GLO	Bauxite mining	Alumina refining	Anode/paste production	Electrolysis	Ingot casting	Total	Primary energy (MJ)	
							R	NR
Electricity	<0.1	0.4	<0.1	9.2	<0.1	9.7	27	104
Process and auxiliary	<0.1	0.7	0.4	2.3	<0.1	3.5	0	18
Thermal energy	<0.1	2.2	0.1	<0.1	0.1	2.4	0	31
Transport	0	0.5	<0.1	0.4	0	0.8	0	10
Total	<0.1	3.8	0.6	11.9	0.2	16.5	27	163

Table 8 - "RoW greenhouse gas emissions split by unit process and process type and primary energy input (renewable (R) and non-renewable energy (NR)) split by process type." (Nunez & Jones, 2015).

RoW	Bauxite mining	Alumina refining	Anode/paste production	Electrolysis	Ingot casting	Total	Primary energy (MJ)	
							R	NR
Electricity	<0.1	0.1	<0.1	4.6	<0.1	4.8	42	55
Process and auxiliary	<0.1	0.7	0.4	2.2	<0.1	3.4	1	18
Thermal energy	<0.1	1.6	0.1	<0.1	0.1	1.8	0	26
Transport	0	0.5	<0.1	0.3	0	0.8	0	10
Total	<0.1	2.8	0.6	7.2	0.2	10.8	44	109

Electricity production for electrolysis, which accounts for 59% of the total GLO and 45% of the total RoW, is the largest contributor to global warming potential (GWP), as shown by a comparison of the values in tables 7 and 8. (Nunez & Jones, 2015).

CHAPTER 5. DISCUSSION AND CONCLUSION

5.1 COMPARIONS TO STEEL

Due to its strength and dependability, steel has been the most popular construction material for a ship's hull for a number of decades. Steel has frequently been a natural best guess in construction of vessels hulls, despite the fact that today a number of other materials are also used. It would be natural to compare aluminum to steel in order to evaluate aluminum as a hull construction material overall.

Weight: Since aluminum has a density that is one third that of steel (2.7 kg/m^3), structures made of aluminum alloy will always be the lightest when compared to steel structures. Compared to steel, aluminum is lighter, but with the same strength. Due to the light weighted aluminium construction, a ship's center of gravity is lowered, resulting in a more stable and seaworthy ship. (Ocean Navigator, 2007).

Steel is heavy, which has the benefit of making a heavy vessel less likely to roll. However, a vessel made of aluminum could be made lighter and perform and function more effectively by adding more ballast. Using aluminum instead of steel can result in significant weight savings, as discussed in chapter 4.2. Assuming equal thickness, rigidity, and stress, table 9 compares steel and aluminum in terms of potential weight savings. Consequently, aluminum-made vessels may potentially lose a significant amount of weight. The possibility of increased load, reduced fuel consumption, and increased speed are just a few benefits of the weight reduction. (Alcan Marine, 2023).

Table 9 - Weight reduction using aluminium vs steel. (Alcan Marine, 2023).

REDUCTION IN WEIGHT OF ALUMINIUM ALLOY STRUCTURES				
Comparison	Criterion	Aluminium	Steel	Potential Saving
Equal thickness	Density	2,7	7,8	66 %
Equal rigidity	Young's modulus	70 000 MPa	210 000 MPa	50 %
Equal stress	Proof stress	215 MPa	355 MPa	43 %

According to tests conducted in the article "aluminum advantages," aluminum has significantly lower towing resistances and hull power than steel. Figure 40 shows the fuel consumption savings per mile and shows how the overall performance improvement of the aluminum hull increases noticeably as vessel speed increases. (Alcan Marine, 2023).

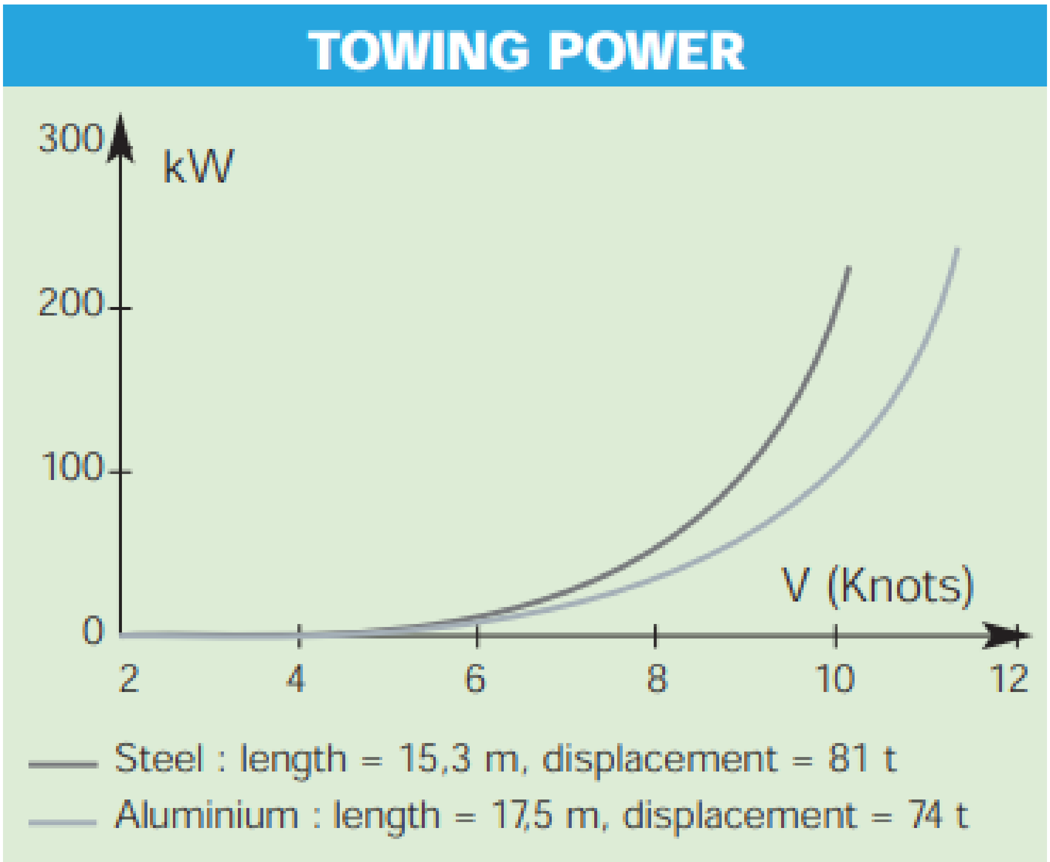


Figure 40 - Towing power for aluminium vs steel. (Alcan Marine, 2023).

Strength: It would have required roughly 50% more plate thickness to construct an aluminum structure with an equivalent strength to steel (with stiffness as a design criterion). Then, an aluminum plate would yield at roughly 351 kPa (N/m^2) (TyreSafe, 2023), which is about 29% greater yield strength than for a steel plate. An aluminum plate would fail at roughly 461 kPa (N/m^2) (TyreSafe, 2023), which is about 12.5% greater ultimate strength than the steel plate. These factors show that the aluminum vessel will be stronger overall and per square area of plate than steel. This is as a result of the aluminum plate being 150% thicker than the steel plate in order to increase stiffness. (Kasten, 2001-2016).

A summary of the different material properties in comparison, including those for steel and aluminum, is shown in table 10.

Table 10 - Material properties comparisons. (Alcan Marine, 2023).

PROPERTIES OF SELECTED ALUMINIUM ALLOYS AND METALS IN CURRENT USE (*)

Property	5086 H111	5083 H111	*Sealium®* (**)	6082 T6	6005A T5	Steel E24	Steel E36	Stainless Steel Z7CN18-09 Annealed	Copper Annealed M20
Density (kg.m^{-3})	2 660	2 660	2 660	2 710	2 700	7 820	7 820	7 900	8 940
Fusion interval (°C)	585/640	574/638	574/638	570/645	607/654	1400/1530	1400/1530	1375/1400	1083
Coefficient of linear expansion 20 à 100 °C (10^{-6}.K^{-1})	23,8	23,8	23,5	23,5	23,6	11,7	11,7	17,5	16,5
Modulus of elasticity (MPa)	70 000	70 000	70 000	70 000	70 000	210 000	210 000	200 000	115 000
Yield strength, $Rp_{0,2}$ (MPa)	120	125	220	260	260	240	360	300	70
Tensile Strength Rm (MPa)	240	275	305	310	285	410	550	660	235
Elongation A %	15	15	10	10	12	24	20	54	45

Formability: Since aluminum is more malleable and elastic than steel, it can take on shapes that steel cannot. In particular, aluminum would be the best material for parts with deep, straight walls. Steel is a very strong and resilient metal, but it generally cannot be stretched to the same extreme dimensional limits as aluminum without cracking. (Hornbacher, 2017-2023) Due to the difference in weight, handling aluminum rather than steel will be quicker and easier when building the hull. Compared to aluminum, steel requires more specialized machinery and heavy grinders. When compared to welding a steel hull, welding an aluminum forestay is simpler and takes only about half as long. (Ocean Navigator, 2007). A downside for aluminium, however, is that the welding equipment is quite a bit more expensive than for steel. With its low melting point, aluminum can also fall victim to melting and burning in case of a fire, unlike steel, which has a much higher melting point and is the most fire-resistant material there is. (Ocean Navigator, 2007).

Corrosion: The greatest quality of aluminum, is its ability to resist corrosion. Aluminum doesn't rust, and it doesn't require paint or other coatings that deteriorate over time. Steel hulls are more prone to rust and corrosion, and they lose 0.004 inches of thickness yearly on average. (Ocean Navigator, 2007) Steel typically needs to be painted or coated to prevent rust and corrosion, which also requires more maintenance. (Hornbacher, 2017-2023). Zink anodes are required for both aluminum and steel vessels to protect against corrosion. Aluminum is very susceptible to copper corrosion while steel is much more resistant to galvanic corrosion. A piece of wire left in the bilge can quickly eat through a hull. In order to ensure insulation, bilges are frequently painted. This is because fasteners must be made of materials like plastic or stainless steel. (Svseeker, u.d.).

Unlike aluminum, steel is exposed to the bacteria that reduces sulfate. In places like bilges, ballast tanks, and fuel tanks, these bacteria may accumulate. A sheet of 5/16-in. steel can be consumed by it in a year. It accelerates corrosion by consuming sulfates and generating sulfides, and if left unchecked, it may result in catastrophic corrosion. (Ocean Navigator, 2007).

Price: As earlier mentioned in this thesis, in the time of writing, the price of steel is approximately NOK 16/per kg or $1,600 per ton (Checkatrade, 2022), while the price of aluminum is approximately NOK 27/per kg or $2,700 per ton (Jagdish Metal, 2023). Although steel is significantly more affordable than aluminum, aluminum makes up for the cost difference through weight savings, as it weighs only a third as much as steel. The ship's ability to move more quickly and consume less fuel is also beneficial because an aluminum hull would have a reduced weight, compared to a steel hull. As a result, when the vessel starts to operate, the costs could potentially be equalized. While the construction materials are an upfront cost, switching from steel to aluminum can reduce on-going costs like fuel. Compared to steel, aluminum has a higher scrap value, which can make up for the higher initial material cost. (Ocean Navigator, 2007).

Energy consumption: Aluminum production requires a lot of energy. According to the article "The Problem with Aluminum," aluminum has an embodied energy of 233 MJ per kg, whereas steel has an embodied energy of 25 MJ per kg. (Brooks, 2012) The difference in production volume between them, where nearly 1,500 million tons of steel were produced globally in 2011 compared to 40 million tons of aluminum, is also caused by the different amounts of energy needed to produce each metal. The energy savings can be offset over the course of the metal's lifetime if aluminum is used in place of steel in transportation because it is three times lighter than steel. (Brooks, 2012).

5.2 COMPARISONS TO CARBON FIBRE

Carbon fiber, shown in figure 41, is a well-known and frequently used construction material for hulls, which makes it relevant for comparisons in this thesis. Carbon elements are long chains of crystalline carbon filaments that are bound together to form carbon fiber, (DragonPlate, 2023) and it contains a composition of composite carbon fiber and epoxy resin. (Tasuns , 2018). The fibers are strong and stiff, and carbon fiber is regarded as the strongest and lightest material because it weighs only half as much as aluminum while having up to three times the strength. Aluminum and steel are unable to match the stiffness and strength of carbon fiber. (MXA Motocross action, 2022).

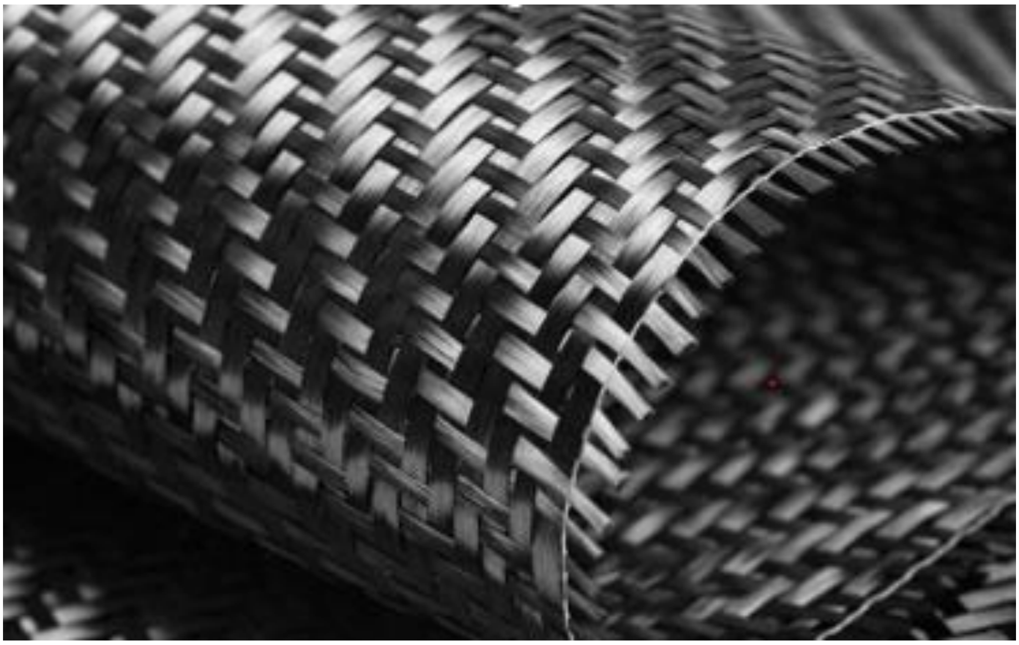


Figure 41 - Carbon fiber. (PUR CARBON, 2020)

Carbon fiber has a density that is two times lower than aluminum and five times lower than steel. As a result, replacing aluminum with carbon fiber will reduce weight by 50%, while replacing steel with carbon fiber will multiply weight reduction by five. (Tasuns , 2018) About 800 MJ of energy are used to produce one kg of carbon fiber, which is very high when compared to both steel and aluminum. (Sunter, R. Morrow III, Cresko, & Liddell, 2015). An illustration shown in figure 42 is made to highlight the difference regarding energy consumption, for aluminium, steel, and carbon fiber.

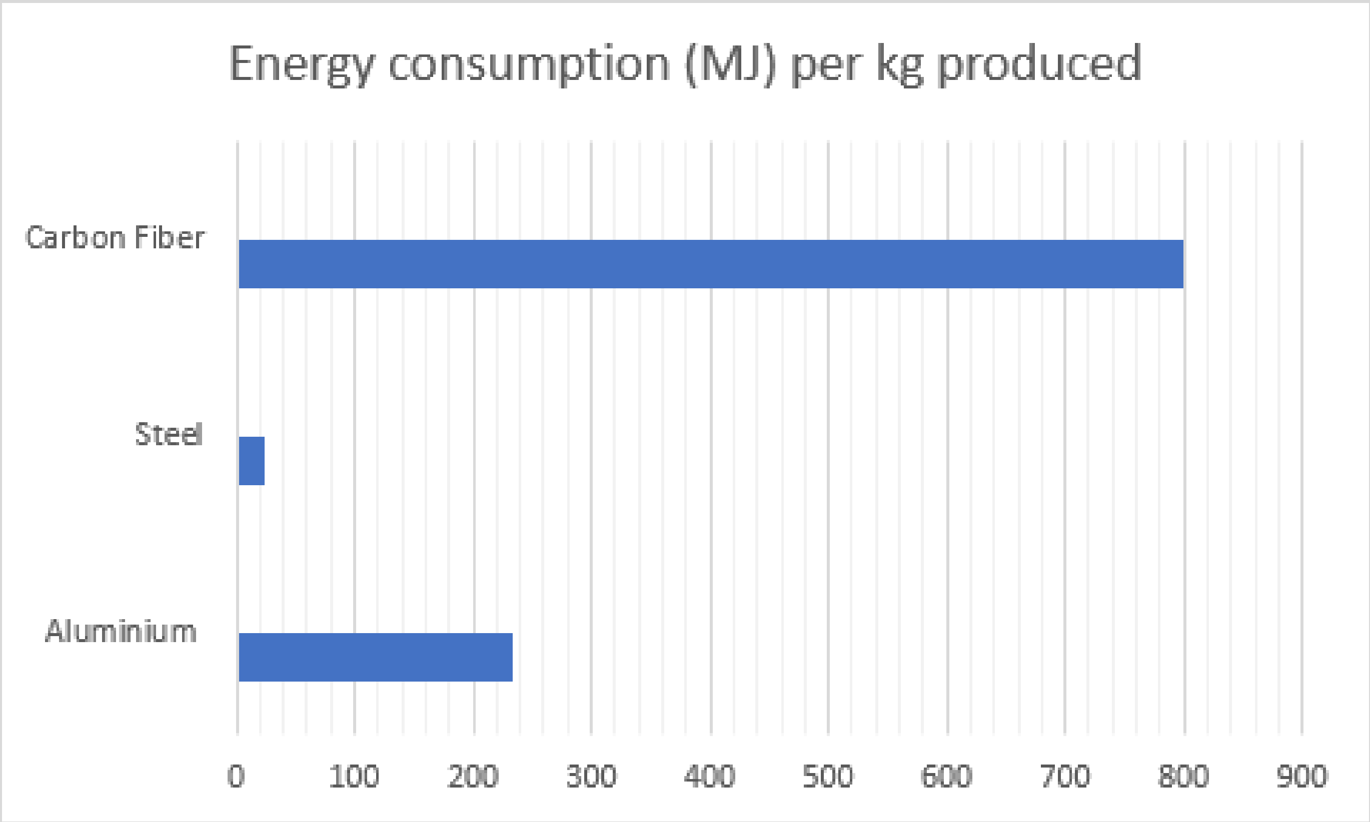


Figure 40 - Energy consumption (MJ) per kg produced. (Knarvik, 2023) (Sunter, R. Morrow III, Cresko, & Liddell, 2015) (Brooks, 2012).

Table 11 - Companions for Aluminium, Steel and Carbon fiber. (Knarvik, 2023) (Milovich, 2013).

Material	**Modulus of Elasticity**	**Tensile Strenght**	**Density**	**Price**
	Metric GPa	*Metric (MPa)*	g/cm^3	*NOK/per kg*
Aluminium	72	380	2,65	27
Steel (Alloy steel AISI 5130)	205	1275	7,85	16
Carbon fiber T700S (epoxy composite)	120	2550	1,57	632

Table 11 is a multiple comparison table, which compare elasticity, tensile strength, density, and price, for aluminium, steel, and carbon fiber.

A material's modulus of elasticity provides information on its resistance, how easily a material can deform in an elastic or non-permanent way and the amount of force needed to deform it. (INSTRON, u.d.).

In this case, steel has the highest resistance (205 GPa), and aluminum has the lowest resistance (72 GPa). With 120 GPa, carbon fiber is in the middle layer.

A material's tensile strength is the highest stress it can withstand while being stretched or pulled without breaking. (THE GUND COMPANY, 2023). In this case, carbon fiber has a tensile strength that is more than six times higher than that of aluminum and has the highest tensile strength of all three materials.

"Density is the mass of a unit volume of a material substance." (Augustyn, u.d.).

The formula of density; $\rho = \frac{m}{v}$

ρ – density,

m – mass,

v – volume

With a density of 2.65 g/cm^3, aluminum is well known to be a lightweight material, but carbon fiber is even more lightweight at 1.57 g/cm^3.

The carbon fiber cost in the table is given with an average number between commercial-grade carbon fiber, which is 330 NOK per kg, and aerospace-grade carbon fiber, which is 935 NOK per kg. (CARBON FIBER GEAR, 2022). While the prices for steel and aluminum are roughly 16 NOK and 27 NOK per kg, respectively, the cost of carbon fiber is much higher at NOK 632 per kg. When comparing the materials, you can see that there are significant differences in price, which is a crucial consideration in construction projects.

In contrast to aluminum, carbon fiber cannot be melted down and reformed. Long, precisely aligned carbon fibers that are fixed inside of a glue-like polymer and cured at high temperatures and pressures give carbon fiber composites their strength. (Harris, 2017). Most of these tough polymers won't melt once they've hardened, so to recover the useful fibers, they must be burned off or chemically broken down. The recycling results in a still light material, but with a significantly reduced strength. (Harris, 2017).

5.3 MEASURES TO IMPROVE ALUMINIUM PRODUCTION

The production of aluminum has nearly doubled over the past ten years, reaching 65 million tons in 2020. Very large amounts of electricity are consumed as a result of this high production volume. (Senanu, Skybakmoen, & Solheim, 2021). While there has been some improvement in aluminum production emissions over time, there is still a long way to go before the 2050 target of zero net greenhouse gas emissions is met. (Senanu, Skybakmoen, & Solheim, 2021). Examining strategies and alternate solutions to reduce emissions at this time is crucial and unavoidable.

Today's used Hall-Héroult technology for aluminum production can be improved to reduce energy consumption and improve CO_2 emissions. Whether changes with regard to cell design, material selection and improvement of process control may apply. (Senanu, Skybakmoen, & Solheim, 2021). Hydro has for a long time worked on several projects in this area, and on that occasion has developed a new technology, Hal4e Ultra. With the help of long-term research and improvements in design and material selection, the cells have been developed to be able to reduce the energy requirement to below 12,000 kWh per kg metal produced, which amounts to an improvement of 10%. (Senanu, Skybakmoen, & Solheim, 2021).

The use of renewable energy sources should be a further area of improvement. The main source of electrical energy in the world is carbon-based. Carbon-based energy sources have very high CO_2 footprints, resulting in an increase in CO_2 emissions. (Senanu, Skybakmoen, & Solheim, 2021). In the case of energy derived from carbon, carbon is burned to produce heat, which is then transformed into electrical energy. In comparison to carbon-based energy, renewable energy, which is primarily used in Norway, accounts for 20% of emissions. (Senanu, Skybakmoen, & Solheim, 2021).

The potential for carbon capture and storage is examined in a project run by SINTEF. This could be accomplished by raising the CO_2 level in the exhaust gases, which would make it possible to recover the heat and reuse it for other purposes, like electricity generation or heating. (Senanu, Skybakmoen, & Solheim, 2021). CO_2 emissions can be decreased by switching from the carbon-based anodes currently in use to inert anodes. When using inert anodes, oxygen is released as anode gas rather than CO_2. However, in order to reduce the CO_2 footprint of this technology, more energy will be needed, which necessitates that the energy be renewable. (Senanu, Skybakmoen, & Solheim, 2021).

5% of the energy used to produce aluminum is used for recycling, resulting in extremely low CO_2 emissions. Because of this, recycling is a highly advantageous method for lowering CO_2 emissions and energy use.

5.4 CONCLUSION

The conclusion of the report is covered in this chapter. The purpose of the thesis was to examine the life cycle of aluminum, as a construction material used to make the hull of a vessel. Although steel has a slightly better reputation for being stronger and a better option, many manufacturers use aluminum to build hulls today. In order to examine the benefits and drawbacks and to obtain a comprehensive picture, this thesis has examined the entire life cycle of aluminum, from cradle to grave.

This chapter concludes the research study by answering the research question mentioned below:

Does aluminum make a good construction material for a vessels hull based on the life cycle analysis, and can it compete with steel? Are there specific advantages associated with aluminum that could be beneficial to the hull of a ship?

Aluminum production requires a lot of energy, a lot more than steel production, which also generates more CO_2 emissions. In exchange, recycling it and creating secondary aluminum only requires 5% of the energy that was previously used, leading to noticeably lower emissions. Despite the fact that producing steel requires less energy and emits fewer emissions than producing aluminum, only about half as much aluminum is needed to build the same hull. The amount of steel versus aluminum used to build the hull could then result in roughly equivalent total energy consumption and emissions.

Compared to steel, aluminum is more malleable and easier and less expensive to handle. With significantly less weight and with the same strength as steel, aluminum is superior in terms of weight. The many positive effects of aluminum's ability to reduce weight include improved cargo space, increased speed, and decreased fuel consumption.

Aluminum is significantly easier to shape, lighter, and easier to handle. Unlike steel, it can be stretched and shaped much further without breaking or losing strength. The high melting point of steel, on the other hand, makes it significantly more heat resistant than aluminum. Because of this, steel serves as a better fire-resistant material. In contrast to steel, which can typically lose 0.004 inches of thickness per year due to rust and corrosion, aluminum has the unusual ability not to rust. Both materials need to be protected from corrosion, and sacrificial anodes like zinc are a good option for this. Maintenance-wise, aluminum is low-maintenance and, in the event of damage, is a material that is relatively simple to fix.

Aluminum's high price and significant energy consumption during production are drawbacks. While requiring significantly less energy to produce, steel is also much more affordable. Aluminum makes up for this later on, though, with weight that is one-third that of steel, increased vessel speed, less fuel consumption, and even simpler operations. Aluminum has a higher scrap rate than steel, but both metals can be recycled with a significant reduction in energy use.

It is safe to draw the conclusion that aluminum is a suitable choice to use as a construction material on a vessel's hull based on the findings of this thesis. In comparison to steel, it will be a material that is equally safe, strong, and appropriate after weighing the advantages and disadvantages.

Additional work is continuously being done with several alternative solutions to reduce CO_2 emissions. Hydro Aluminum has been creating new technologies that reduce emissions and improve energy use for a while. A greater focus on the use of renewable energy sources globally and the use of techniques like inert anodes that release oxygen rather than CO_2 would both be efficient substitute measures. Reusing heat that is produced during the aluminum production and reducing emissions can both be accomplished by utilizing new technologies and making carbon capture a reality.

References

Abdollahi, J., Emrani, N., Chahkandi, B., Montazeri, A., Aghlmand, R., & Gheibi, M. (2021, 06 26). Environmental impact assessment of aluminium production using the life. *cycle assessment tool and multicriteria analysis. Ann Environ Sci Toxicology 5(1): 059-066. DOI: https://dx.doi.org/10.17352/aest.000038* , p. 9.

Aid, C. (2022, 12 22). *Profit before people and planet: How economic policies and corporate profit maximisation perpetuate the unsustainable exploitation of the Brazilian Amazon and its people*. Retrieved from Reliefweb: https://reliefweb.int/report/brazil/profit-people-and-planet-how-economic-policies-and-corporate-profit-maximisation-perpetuate-unsustainable-exploitation-brazilian-amazon-and-its-people

Alcan Marine. (2021, 07). *FIRE RESISTANCE OF ALUMINIUM* . Retrieved from Almet.marine.com: https://almet-marine.com/wp-content/uploads/2021/07/Ch09-fire-resistance-of-aluminium.pdf

Alcan Marine. (2023). *Aluminium's advantages*. Retrieved from Almet-marine.com: https://almet-marine.com/wp-content/uploads/2021/07/Ch02-aluminium-s-advantages.pdf

Aluminium INSIDER. (2023, 02 19). *hydro-karmoy-metal-tapping-vehicle*. Retrieved from Aluminium INSIDER: https://aluminiuminsider.com/norsk-hydro-posts-record-high-adjusted-ebitda-in-third-quarter/hydro-karmoy-metal-tapping-vehicle/

Aluminium Life Cycle. (2020, 09 03). Retrieved from ALUTECH SYSTEMS: https://alutechsystems.co.uk/aluminium-life-cycle/

Aluminium Marine Consultants. (2019-2022). *Aluminium Marine Consultants are the UK's leading aluminium boat builders, providing innovative and bespoke work boat vessel construction and design since 2007.* Retrieved from Aluminium-boats.com: https://www.aluminium-boats.com/

Aluminium Marine Consultants. (2019-2022). *Industry leading wind farm support vessels* *designed and built to exceed expectations*. Retrieved from Aluminium-boats.com: https://www.aluminium-boats.com/windfarm-support

Aluminium Stewardship Initiative (ASI). (2023). *Vision, Mission and Values*. Retrieved from ASI - aluminium stewardship initiative: https://aluminium-stewardship.org/about-asi/vision-mission-values

Amrani, S., Kocaefe, D., Kocaefe, Y., Bhattacharyay, D., Bouazara , M., & Côté , J. (2021, 01 25). Effect of carbon anode production parameters on anode cracking. *Effect of carbon anode production parameters on anode cracking*.

ASA, Norsk Hydro. (2023). *Bauksitt*. Retrieved from Hydro.com: https://www.hydro.com/no-NO/aluminium/produkter/bauksitt-og-alumina/bauksitt/

Assadian, M. (2022). Utslipp til Ytre Miljø. *Utslipp til Ytyre Miljø for Hydro Karmøy*. Norge: Hydro Karmøy.

Augustyn, A. (n.d.). *Density*. Retrieved from BRITANNICA: https://www.britannica.com/science/density

Baird Maritime. (2021, 05 25). *VESSEL REVIEW | HAVØRNA – COMPACT FISH FARM WORKBOAT ENTERS SERVICE WITH NORWAY'S LERØY AURORA*. Retrieved from Bairdmaritime.com: https://www.bairdmaritime.com/fishing-boat-world/aquaculture-world/vessel-review-havorna-compact-fish-farm-workboat-enters-service-with-norways-leroy-aurora/

Benson, S., & Downes, J. (2011, 03 18). Ultimate strength characteristics of aluminium plates for high speed vessels. *Ships and Offshore Structures, 6:1-2, 67-80, DOI: 10.1080/17445302.2010.529696*, p. 38.

Berge, S. (2011). Materialteknologi. In S. Berge, *Havromsteknologier* (p. 26). Trondheim: NTNU - Institutt for marin teknologi.

British Plastic Federation. (n.d.). *Life Cycle Analysis (LCA) - A Complete Guide to LCAs*. Retrieved from BPF - British plastics federation: https://www.bpf.co.uk/sustainable_manufacturing/life-cycle-analysis-lca.aspx

Brooks, G. (2012, 05 25). *The trouble with aluminium*. Retrieved from https://theconversation.com/the-trouble-with-aluminium-7245#:~:text=It%20is%20true%20that%20a,GJ%20per%20tonne%20for%20steel.

Bryhn, R., & Gram, T. (2023, 01 23). *Norsk Hydro*. Retrieved from Store Norske Leksikon: https://snl.no/Norsk_Hydro#:~:text=Verket%20kan%20produsere%20585%20000,Raufoss)%20og%20mange%20andre%20land.

Brynjulfsen, M. (2020). Introduksjon til prosessmetallurgien i Holmestrand. Holemstrand, Norge: Hydro Aluminium/Speira Holmestrand.

CARBON FIBER GEAR. (2022). *Carbon Fiber vs. Aluminum: What Are the Pros and Cons*. Retrieved from CARBON FIBER GEAR: https://carbonfibergear.com/blogs/carbonfiber/carbon-fiber-vs-aluminum

Checkatrade. (2022, 07 24). *Steel building prices*. Retrieved from Checkatrade: https://www.checkatrade.com/blog/cost-guides/steel-building-prices/

Citimarine. (2022, 12 01). *When to Use Zinc Anodes or Aluminum Anodes on Your Boat*. Retrieved from CITIMARINE STORE: https://citimarinestore.com/citiguide/when-to-use-zinc-anodes-over-aluminum-anodes-on-a-boat/

CPM. (2023). *Galvanic Corrosion (Bi-Metallic Corrosion)*. Retrieved from CPM: https://www.cmp-products.com/cable-cleats/technical-cable-cleats/galvanic-corrosion-cable-cleats/

D&D Coatings. (2019, 05 26). *What is Pitting Corrosion?* Retrieved from D&D Coatings: https://www.ddcoatings.co.uk/2276/what-is-pitting-corrosion

Danbolt, I. L. (2022, 05 25). *Klimaendringer*. Retrieved from FN-SAMBANDET: https://www.fn.no/tema/klima-og-miljoe/klimaendringer

DragonPlate. (2023). *WHAT IS CARBON FIBER?* Retrieved from DragonPlate.com: https://dragonplate.com/what-is-carbon-fiber

Endresen, P. T. (2020, 02 17). Karmøy Rolling Mill (KRM) - Åpningsmøte - vår virksomhet.

Karmøy Rolling Mill (KRM) - Åpningsmøte - vår virksomhet. Karmøy, Norge: KRM.

Falde, N. (2018, 08 16). *How is Aluminum Recycled: The Recycling Process*. Retrieved from Greentumble.com: https://greentumble.com/how-is-aluminum-recycled

FASTENAL. (2023). *Galvanic Corrosion*. Retrieved from FASTENAL: https://www.fastenal.com/fast/services-and-solutions/engineering/corrosion

FOAM Sealant. (2016, 06 08). *High and Low Modulus of Elasticity: What are the Differences?* Retrieved from FOAM Sealant: https://foamsealant.com.au/high-and-low-modulus-of-elasticity-what-are-the-differences/#:~:text=A%20softer%20material%20with%20a,that%20can%20absorb%20heavy%20loads.

Green Car Congress. (2018, 01 29). *Hydro starts aluminum production at HAL4e pilot plant; highest energy efficiency, smallest CO2 footprint*. Retrieved from Green Car Congress: https://www.greencarcongress.com/2018/01/20180129-hydro.html

Gyda. (n.d.). *Aluminium*. Retrieved from Gyda.biz: https://gyda.biz/om-gyda/hvorfor-aluminium

Gyda. (n.d.). *Aluminium*. Retrieved from Gyda: https://gyda.biz/om-gyda/hvorfor-aluminium

Haraldsson, J. (2020). *Improved Energy Efficiency in the Aluminium Industry and its Supply Chains.* Linköping: Division of Energy Systems, Department of Management and Engineering, Linköping University.

Harris, M. (2017, 03 22). *Carbon fibre: the wonder material with a dirty secret*. Retrieved from The Guardian: https://www.theguardian.com/sustainable-business/2017/mar/22/carbon-fibre-wonder-material-dirty-secret

Helmenstine, A. M. (2019, 02 06). *Aluminum or Aluminium Alloys*. Retrieved from ThoughtCo: https://www.thoughtco.com/aluminum-or-aluminium-alloys-603707

Hornbacher, A. (2017-2023). *ALUMINUM VS STEEL: WHICH METAL IS BETTER?* Retrieved from Wenzel Metal Spinning: https://www.wenzelmetalspinning.com/steel-vs-aluminum.html#:~:text=Aluminum%20is%20a%20very%20desirable,is%20the%20material%20of%20choice.

Hovland, K. M. (2020, 12 21). *Hydros Karmøy-teknologi besto testen: – En milepæl for oss*. Retrieved from E24: https://e24.no/energi-og-klima/i/OQyGaV/hydros-karmoey-teknologi-besto-testen-en-milepael-for-oss

How much hydrogen will be needed to replace coal in making steel? (2020, 11 04). Retrieved from CARBON COMMENTARY: https://www.carboncommentary.com/blog/2020/11/4/how-much-hydrogen-will-be-needed-to-replace-coal-in-making-steel#:~:text=The%20energy%20value%20of%20the,making%20the%20exteriors%20of%20cars.

Husband, T. (2012, 04). *Aluminum Recycling*. Retrieved from ACS Chemistry for life: https://www.acs.org/education/resources/highschool/chemmatters/past-issues/archive-2011-2012/aluminum-recycling.html

HYDAL ALUMINIUM PROFILER. (n.d.). *Legeringer*. Retrieved from HYDAL ALUMINIUM PROFILER: https://hap.hydal.com/download-routerfile.php?temp_id=95&file_id=1776

Hydro. (2020, 12 21). *Hydro Karmøy Technology Pilot successfully verified*. Retrieved from Hydro.com: https://www.hydro.com/en/media/news/2020/hydro-karmoy-technology-pilot-successfully-verified/

Hydro. (2021, 06 16). *Fakta om aluminium*. Retrieved from Hydro.com: https://www.hydro.com/no-NO/aluminium/om-aluminium/fakta-om-aluminium/

Hydro. (2023). *Alumina*. Retrieved from Hydro.com: https://www.hydro.com/en-NO/aluminium/products/bauxite--alumina/alumina/

Hydro. (2023, 03 03). *Aluminium recycling*. Retrieved from Hydro.com: https://www.hydro.com/en-NO/aluminium/about-aluminium/aluminium-recycling/

Hydro. (2023). *Alunorte*. Retrieved from Hydro.com: https://www.hydro.com/en-NO/about-hydro/hydro-worldwide/north-america/brazil/barcarena/alunorte/?gclid=CjwKCAjwo7iiBhAEEiwAsIxQEaajWU3sA4xOnHomM2ZUhensYRoMWXshNeLvDRXPDf22NHLwE6ywxBoCuGQQAvD_BwE

Hydro. (2023). *Always meeting your requirements*. Retrieved from Hydro: https://www.hydro.com/en/aluminium/products/extruded-profiles/services/meeting-your-quality-needs/

Hydro Aluminium. (2001). Aluminium i det marine miljø. *Aluminium i det marine miljø*. Norge - OSLO: Hydro Aluminium Vekst.

Hydro Aluminium a.s, Elkem Aluminium ANS, Sør-Norge Aluminium AlS. (1995). *NORSK .ALUMINIUMINDUSTRI.* Oslo: Hydro Aluminium a.s, Elkem Aluminium ANS, Sør-Norge Aluminium AlS.

Hydro Aluminium. (n.d.). ALUMINIUM som konstruksjonsmateriale offshore. *ALUMINIUM som konstruksjonsmateriale offshore for Hydro Aluminium Offshore*. Norge: Hydro Aluminium.

Industriskolen. (2018, 11 19). *Framstilling av aluminium*. Retrieved from ndla: https://ndla.no/subject:1:8c5a9fdd-4fa4-456b-9afe-34e7e776b4e7/topic:1:0e750f7b-6b9c-4abd-8c0d-780ca55be4c4/topic:1:24c3be2b-621b-4d85-a6c1-7baee6ab6375/resource:1:44921

INSTRON. (n.d.). *Modulus of Elasticity*. Retrieved from INSTRON: https://www.instron.com/en/resources/glossary/m/modulus-of-elasticity

Iversen, O. L. (05, 12 12). *Aluminium til sjøs*. Retrieved from Ovni.no: https://www.ovni.no/pdf/Aluminium_til_sjo_Av_OLI_051212.pdf

Jagdish Metal. (2023). *ALUMINIUM 5083 SHEET PRICE LIST*. Retrieved from https://www.jagdishmetalindia.com/aluminium-5083-sheet-bar-price-list.html

Johansen, H. (2012, 06 08). Aluminium. *Aluminium*. Norge: Høgskolen i Gjøvik.

Kallestad, T. (n.d.). Aluminium, mulighetenes metall. *Aluminium, mulighetenes metall*.

Norge: ÅSV, Nordisk Aluminium, Norge.

Kasten, M. (2001-2016). *Strength of Aluminum vs Strength of Steel*. Retrieved from CASTEN MARINE DESIGN: http://www.kastenmarine.com/alumVSsteel.htm

Keilman, T. (2023, 01 16). *Norsk industri må ha en tydeligere rolle i fremtidens energisystem*. Retrieved from Forskningsrådet: https://www.forskningsradet.no/sok-om-finansiering/hvem-kan-soke-om-finansiering/forskningsorganisasjoner/Prosjekter-forskningsorganisasjoner/norsk-industri-ma-ha-en-tydeligere-rolle-i-fremtidens-energisystem/

Keller, F., Sulger, P. O., Meier, D. W., Severo, D. S., & Gusberti, V. (2010). SPECIFIC ENERGY CONSUMPTION IN ANODE BAKE FURNACES. *SPECIFIC ENERGY CONSUMPTION IN ANODE BAKE FURNACES - Light Metals 2010 - TMS (The Minerals, Metals & Materials Society)*, p. 6.

Kermeli, K., Weer, P.-H. t., Crijns-Graus, W. H., & Worrell, E. (2014, 10 31). Energy efficiency improvement and GHG abatement in the global production of primary aluminium. *Energy Efficiency 8, 629–666 (2015). https://doi.org/10.1007/s12053-014-9301-7*. Retrieved from Energy Efficiency (2015) 8:629–666. DOI 10.1007/s12053-014-9301-7. - SpringerLink: https://link.springer.com/article/10.1007/s12053-014-9301-7

Khedmati, M. R., & Hosseinabadi,, O. F. (2021, 05 24). A review on ultimate strength of aluminium structural elements and systems for marine applications. *A review on ultimate strength of aluminium structural elements and systems for marine applications*. Iran: Department of Maritime Engineering, Amirkabir University of Technology. Retrieved from https://www.sciencedirect.com/topics/engineering/5000-series-alloy

Kimple. (2021, 01 15). *Hvorfor aluminiumslegering høyhastighetsbåter favoriseres av båtentusiaster*. Retrieved from KIMPLE: https://no.kimpleboating.com/news/why-aluminum-alloy-high-speed-boats-are-favore-54838351.html

Knarvik, M. (2023, 04 24). Energy concumption (MJ) per kg produced. Kopervik, Norway.

Kvande, H. (2014). The Aluminum Smelting Process. *Journal of occupational and environmental medicine / American College of Occupational and Environmental Medicine*, 4.

Latin-amerikagruppene i Norge. (2021, 03 04). *HYDROS LIVSFARLIGE PROFITTJAG*. Retrieved from Latin-amerika gruppene i Norge: https://www.latin-amerikagruppene.no/artikkel/2021/03/04/hydros-livsfarlige-profittjag

LEADRP. (2023, 01 24). *A Complete Guide to Aluminum Extrusion*. Retrieved from LEADRP: https://leadrp.net/blog/a-complete-guide-to-aluminum-extrusion/

Made-in-china. (1998-2023). *Prebaked Carbon Anode Price*. Retrieved from Made-in-china.com: https://www.made-in-china.com/products-search/hot-china-products/Prebaked_Carbon_Anode_Price.html

Maximpact. (2012-2023). *Energy Efficiency and Consumption in the Aluminium Sector*. Retrieved from MAXIMPACT.COM: https://www.maximpact.com/energy-efficiency-aluminium/

MBHydraulikk AS. (n.d.). *Kort om sjøvassbestandig aluminium*. Retrieved from MBHydraulikk AS: https://www.mbh.no/kort-om-sjovassbestandig-aluminium/

MecaniCalc. (2014-2023). *Mechanical Properties of Materials*. Retrieved from MecaniCalc: https://mechanicalc.com/reference/mechanical-properties-of-materials

MILJØDIREKTORATET. (2021). *Hydro Aluminium Karmøy*. Retrieved from Norskeutslipp.no: https://www.norskeutslipp.no/no/Diverse/Virksomhet/?CompanyID=5121

Miljødirektoratet, K. . (2022, 09 28). *Miljømål 5.2*. Retrieved from Miljøstatus: https://miljostatus.miljodirektoratet.no/miljomal/klima/miljomal-5.2

Milovich, D. (2013). *How much lighter is carbon fiber than steel and aluminum? How much stronger is it?* Retrieved from Quora: https://www.quora.com/How-much-lighter-is-carbon-fiber-than-steel-and-aluminum-How-much-stronger-is-it

MXA Motocross action. (2022, 11 11). *Ti Ting Du Trenger Å Vite Om Karbonfiber*. Retrieved from https://motocrossactionmag.com/no/10-ting-du-trenger-%C3%A5-vite-om-karbonfiber-hvordan-du-kan-ta-vare-p%C3%A5-det/

Myloveiw. (2023). *Aluminium hull of a super sailing yacht. air frame. shipbuilding*. Retrieved from Myloveiw: https://myloview.com/sticker-aluminium-hull-of-a-super-sailing-yacht-air-frame-shipbuilding-no-D97A75A

Nagwa. (2023). *Lesson Explainer: Extracting Aluminum*. Retrieved from Nagwa: https://www.nagwa.com/en/explainers/213180242428/

Nickelsen, T. (2019, 05 22). *Hydro i regnskogen: Først rasere, så rekonstruere*. Retrieved from Forskning.no: https://forskning.no/klima-miljogifter-miljovern/hydro-i-regnskogen-forst-rasere-sa-rekonstruere/1339193

Nilsen, A. A. (2018, 11 29). *Disse hindrene må Hydro passere for å løse Brasil-krisen*. Retrieved from E24: https://e24.no/boers-og-finans/i/P3QBA6/disse-hindrene-maa-hydro-passere-for-aa-loese-brasil-krisen

NordicSteel. (2023). *En guide til aluminium: 5 fordeler ved å velge aluminium*. Retrieved from Nordic Steel - parts of great solutions: https://www.nordicsteel.no/fagartikler/5-fordeler-ved-a-velge-aluminium

Nunez, P., & Jones, S. (2015). Cradle to gate: life cycle impact of primary aluminiumproduction. *Int J Life Cycle Assess 21, 1594–1604 (2016). https://doi.org/10.1007/s11367-015-1003-7*, 11.

Ocean Navigator. (2007, 07 27). *Aluminum and Steel, one designer’s view*. Retrieved from Oceannavigator.com: https://oceannavigator.com/aluminum-and-steel-one-designers-view/

Ocean Navigator. (2007, 07 27). *Aluminum and Steel, one designer’s view*. Retrieved from OCEAN NATIGATOR - THE VOYAGER'S RESOURCE: https://oceannavigator.com/aluminum-and-steel-one-designers-view/

Offshore Wind. (2023). Retrieved from OMA Båtbyggeri: https://www.oma.no/offshore-wind/

Onu, P., Ikumapaya, O. M., Akinlabi, E., & Olatunji, A. (2020, 06). Rolling operation in metal forming; Process and Principles - A brief study. *Materials Today: Proceedings · June 2020*, p. 7.

Panalytical, M., & AZO Materials. (2020, 10 06). *How On-Line Aluminum Production Can Help with Particle Size Analysis*. Retrieved from AZO MATERIALS: https://www.azom.com/article.aspx?ArticleID=19705

Pedersen, B., & Kaland, T. (2023, 01 12). *Aluminium*. Retrieved from snl.no: https://snl.no/aluminium

Peng, T., Ou, X., Yan, X., & Wang, G. (2019, 02). Life-cycle analysis of energy consumption and GHG emissions of aluminium production in China. *Energy Procedia*, pp. Volume 158, Pages 3937-3943.

Promek. (2023). *KAPASITET, TEKNOLOGI OG PROSESS*. Retrieved from Promek: https://www.promek.no/produksjon

PUR CARBON. (2020, 07 15). *WHAT IS CARBON FIBER? HOW IS IT MADE AND IS IT INDESTRUCTIBLE?* Retrieved from PUR CARBON: https://pur-carbon.com/blogs/news/what-is-carbon-fiber-how-is-it-made-and-is-it-indestructible

RATSON Shipbuilding. (2019, 11 19). *Steel Boat VS Aluminum Boat*. Retrieved from RATSON : https://www.ratson.com/en/home/infocenterdetail/id/64

RISMA. (2023). *Hvorfor er ISO-standarder så viktige?* Retrieved from RISMA: https://www.rismasystems.com/no/ressurser/artikler/hva-er-fordelene-med-en-iso-standard

Rustad, M., & Kleeb, M. (2023, 05 07). *Fem år etter Hydro-skandalen i Brasil: – Som om vi ikke eksisterer*. Retrieved from E24: https://e24.no/energi-og-klima/i/JQL1jj/fem-aar-etter-hydro-skandalen-i-brasil-som-om-vi-ikke-eksisterer?referer=https%3A%2F%2Fwww.vg.no

Rustad, T. (2021, 08 11). *Karbon – der eventyret starter*. Retrieved from Aura Avis: https://www.auraavis.no/karbon-der-eventyret-starter/f/5-5-295633

Samarasekera, I. (2003). Hot Rolling. *Centre for Metallurgical Process Engineering and University of British Columbia, Vancouver, Canada*.

SaveMyExams - Caroline. (2015-2023). *9.3.3 Extraction of Aluminium from Bauxite*. Retrieved from SaveMyExams: https://www.savemyexams.co.uk/igcse/chemistry/cie/23/revision-notes/9-metals/9-3-extraction-of-metals/9-3-3-extraction-of-aluminium-from-bauxite/

Senanu, S., Skybakmoen, E., & Solheim, A. (2021, 07 02). *Sju veier til grønnere aluminium*. Retrieved from SINTEF: https://www.sintef.no/siste-nytt/2021/sju-veiertilgronnere-aluminium/

SlideShare. (2022, 12 16). *Rolling process*. Retrieved from Slideshare: https://www.slideshare.net/rmrm64/rolling-processpdf

Sotere. (2022, 03). *Hva har metallemballasje med regnskogen å gjøre?* Retrieved from Sotere.no: https://sortere.no/hvorfor/hva-har-metallemballasje-med-regnskogen-a-gjore

Speira. (2022). *Aluminium solutions for shipbuilding*. Retrieved from Speira.com: https://experience.speira.com/speira-via-maris/

Speira. (2023). *Shipbuilding*. Retrieved from Speira.com: https://www.speira.com/markets-products/shipbuilding-transport/shipbuilding/

Speira. (2023). *Substainability*. Retrieved from Speira.com: https://www.speira.com/sustainability/

Sunter, D., R. Morrow III, W., Cresko, J., & Liddell, H. (2015, 07). THE MANUFACTURING ENERGY INTENSITY OF CARBON FIBER REINFORCED POLYMER COMPOSITES AND ITS EFFECT ON LIFE CYCLE ENERGY USE FOR VEHICLE DOOR LIGHTWEIGTING. *20th International Conference on Composite Materials*, 10.

Svseeker. (n.d.). *Steel vs Aluminum*. Retrieved from Svseeker: https://svseeker.com/steel_or_aluminum.htm

Tasuns . (2018, 04 18). *Aluminium Vs Karbonfiber Sammenligning Av Materialer*. Retrieved from Tasuns.com: http://no.custom-composite.com/info/aluminium-vs-carbon-fiber-comparison-of-materi-25709559.html#:~:text=En%20komponent%20laget%20av%20standard,og%20har%2060%25%20mer%20styrke.

Teknisk Ukeblad. (2018, 03 05). *Hydro bytter sjef for å løse krisen i Brasil*. Retrieved from Teknisk ukeblad: https://www.tu.no/artikler/hydro-bytter-sjef-for-a-lose-krisen-i-brasil/431891

THE GUND COMPANY. (2023). *Understanding Tensile Strength*. Retrieved from THE GUND COMPANY: https://thegundcompany.com/understanding-tensile-strength/

Thyssenkryupp. (2023). *Extraction of aluminum*. Retrieved from Thyssenkrupp: https://www.thyssenkrupp-materials.co.uk/how-is-aluminum-made

Torterat, C. (2021, 03 09). *The construction of metal boats, the ally of the great voyage*. Retrieved from BoatNews: https://www.boatsnews.com/story/36326/the-construction-of-metal-boats-the-ally-of-the-great-voyage

TyreSafe. (2023). *Conversion table*. Retrieved from TyreSafe: https://www.tyresafe.org/tyre-advice/tyre-pressures/tyre-pressures-explained/

UC RUSAL. (n.d.). *What is aluminium*. Retrieved from UC RUSAL, leader of the global aluminum industry.: https://www.aluminiumleader.com/about_aluminium/what_is_aluminum/

Universitetet i Oslo. (n.d.). *Aluminium*. Retrieved from Periodesystemet.no: https://www.periodesystemet.no/grunnstoffer/aluminium/index.html

Valvik, M. E. (2018, 10 03). *Hydro stenger tre anlegg i Brasil: - En ganske dramatisk situasjon*. Retrieved from Aftenposten: https://www.aftenposten.no/okonomi/i/0Ey10g/hydro-stenger-tre-anlegg-i-brasil-en-ganske-dramatisk-situasjon

Velling, A. (2020, 05 20). *Aluminium Corrosion & Its Different Types*. Retrieved from Fractory: https://fractory.com/aluminium-corrosion/

Vu, D. T. (2023). *Corrosion resistance properties of aluminum alloys*. Retrieved from Vietnam Cast Iron: https://vietnamcastiron.com/aluminum-alloys-corrosion-resistance/

Wang, M. J. (2016). *The Environmentalhe footprint of semi-fabricated aluminium products in North America.* The aluminium assosiation. Retrieved from https://www.aluminum.org/sites/default/files/2022-01/2022_Executive-Summary_Semi-Fab_LCA.pdf

World of Chemicals. (2023). *Manufacturing of alumina through Bayer process*. Retrieved from World of Chemicals: https://www.worldofchemicals.com/591/chemistry-articles/manufacturing-of-alumina-through-bayer-process.html

YAMARIN cross. (2023). *Maling og bunnstoff-behandling av aluminiumbåtens bunn*. Retrieved from YAMARIN CROSS: https://cross.boats/no/maling-og-bunnstoff-behandling-av-aluminiumbatens-bunn